

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

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ABSTRACT

Engineers at Active Power have combined three mature energy-storage technologies into a new system designed to replace lead-acid batteries in many applications.

THE NEED FOR A NEW ENERGY STORAGE TECHNOLOGY

For a century or more, the telephone industry has been using lead-acid batteries with reasonable success in Central Office applications. Lead-acid batteries can be reliable in an environment of climate-controlled rooms, multiple redundant strings of 24 cells, rigorous maintenance and relatively benign rates of charge and discharge. However, they have been less successful in other applications. For example, data centers use batteries in 240-cell strings – ten times the number of series connections of their telecom counterparts – so the risk of failure is much higher. UPS batteries usually have little or no redundancy, and are subject to heavy cycling loads and fast rates of charge and discharge. Lead-acid batteries also face the issue of disposal and recycling of their lead content.

FLYWHEELS: THE FIRST ALTERNATIVE

In the late 1990s, flywheel energy storage systems became commercially viable for replacing UPS battery cabinets. These systems have proven rugged, reliable, environmentally benign and very power-dense.

Flywheels have been successfully used as a “bridging” energy source, to enable the UPS to continue operating long enough to transition to the backup generator or alternative utility source. They have also been used to “harden” Valve-Regulated Lead-Acid (VRLA) battery cabinets – isolating the batteries from the short-term discharges and step loads that can shorten battery life. However, the relatively short backup times have put flywheels at a perceived disadvantage to batteries in data center and telecom applications. Flywheels have achieved good success in other industries, such as manufacturing and broadcast, where customers primarily want a reliable transfer of the critical load to the backup genset.

STARTING WITH A CLEAN SHEET OF PAPER

The engineers at Active Power decided to take a different approach, beginning with the key requirements: a battery-replacement technology must be safe, reliable, non-toxic, and compact (high energy density). It should have low installed cost and low life-cycle cost.

Compressed air storage is safe, non-toxic and energy-dense at high pressures. Round-trip efficiency is only fair due to heat rejection during compression, but some of this heat may be reclaimed during gas expansion. Recharge times of large pressure vessels is also a disadvantage.

By comparison, thermal storage has excellent energy density – up to 3 times more joules/cubic foot than lead-acid batteries. Unfortunately the research on direct thermoelectric conversion is still in its infancy. Approaches based on sensible (change of temperature) or latent (change of state) heat conversion are more practical in the near term. Table 1 shows the relative strengths and weaknesses of batteries, flywheels, compressed air and thermal energy as applied individually.

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	1.0-1.4	1.4	5.0	5.0

* 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-2004, only two CAES plants have been completed and placed in operation.

Figure 1 below illustrates the key system components and the flow of air through the system.

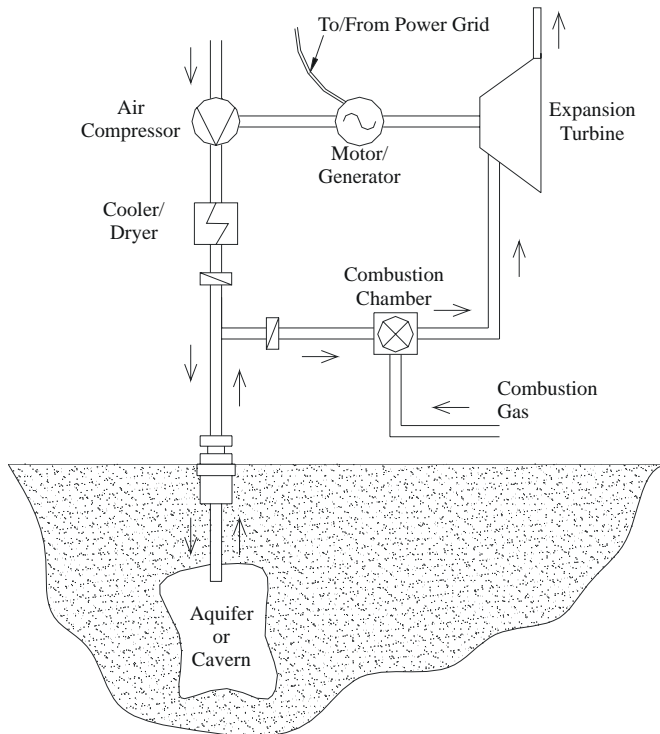


FIGURE 1

COMPRESSED-AIR ENERGY STORAGE (CAES)

One obvious limitation of the CAES technology is that it requires an unused 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.

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. 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.

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 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, magnetic bearings (to levitate the wheel), integrated flywheel/motor generator devices, 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 at least 3 seconds of backup power at full load.

Expansion Turbine

The heated compressed air is used to spin a simple 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 can be extremely simple and compact. The low inertia enables it to reach full operating speed (70,000 rpm) in less than two seconds.

The Complete TACAS System

Figure 2 (next page) 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 TACAS detects a longer outage, it activates the control valves and sends compressed air through the thermal

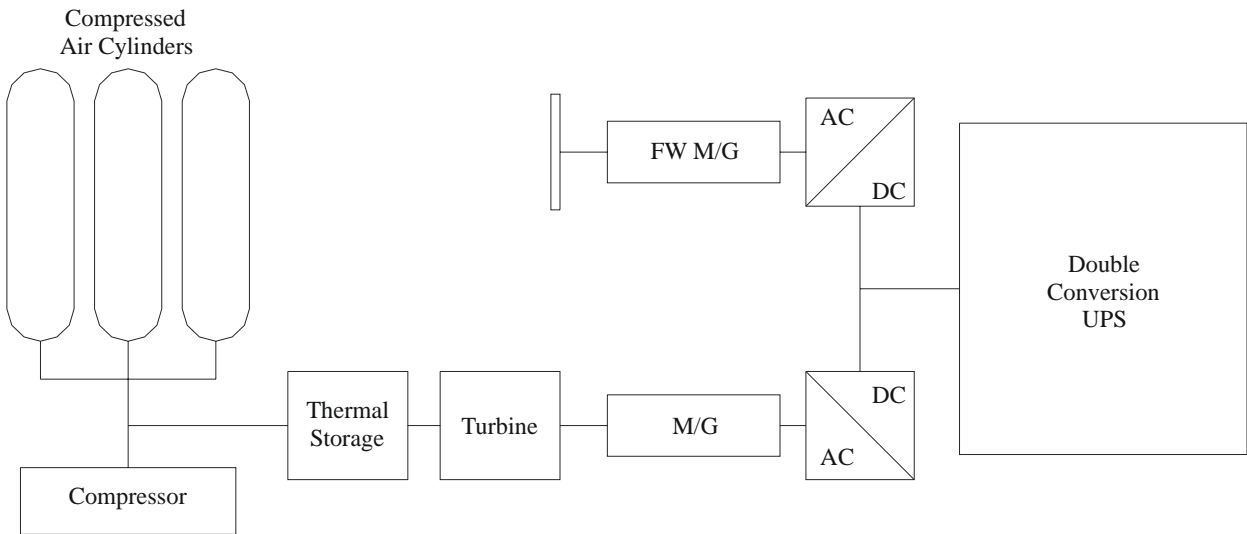


FIGURE 2
THERMAL AND COMPRESSED-AIR STORAGE (TACAS) DIAGRAM

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 TACAS 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.

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: Thermal, Compressed-Air & FW
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 app.	3-12 years*	20 years	20 years
Environmental	Toxic	Benign	Benign
Installed Cost	1.0-1.4	1.4	1.4

* 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

Some aspects of testing the TACAS concept were relatively simple. The team knew they could find many off-the-shelf products to create the first working model: standard compressed-air bottles, air compressor, process-control air valves, turbine, alternator, etc.

The difficult part was creating the mathematical model to predict performance of the completed system, to determine what could be purchased off the shelf and what needed to be designed from scratch.

One of the biggest design-from-scratch tasks 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 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.

What Should This Product Do?

The next step was to create a realistic set of expectations for what the eventual product should be. These were put into the Marketing Requirements Document (MRD). The MRD specified certain general features of TACAS:

- Operate as a normal battery cabinet with the three-phase UPS products of all major manufacturers that employ a standard DC bus voltage.

- Be simple to operate, requiring no operator input except turning the handle of the DC disconnect switch.
- Operate in a wide range of ambient temperatures, from 0-40° C.
- Provide a realistic 20-year life expectancy, with a well-defined schedule of maintenance and replacement of consumables.
- Provide better reliability than lead-acid batteries, and provide alarms to warn operators of present or impending failures.
- Be a good neighbor, with ambient noise in all modes (including compressed-air recharge) not to exceed 70 dBA at 1 meter.
- Be a socially responsible product, built of completely recyclable and non-toxic materials.

In addition to general requirements, the MRD gave specific output ratings of the first commercial product to be built:

- Support a 100 kVA UPS system for approximately 15 minutes at full load. This requires a TACAS output power rating of approximately 84 kW.
- Support lower power ratings for longer run times.
- Support the typical DC bus requirements of both North American and European UPS products. Their nominal ratings are 480 VDC and 400 VDC respectively.
- Be completely self-contained in the base

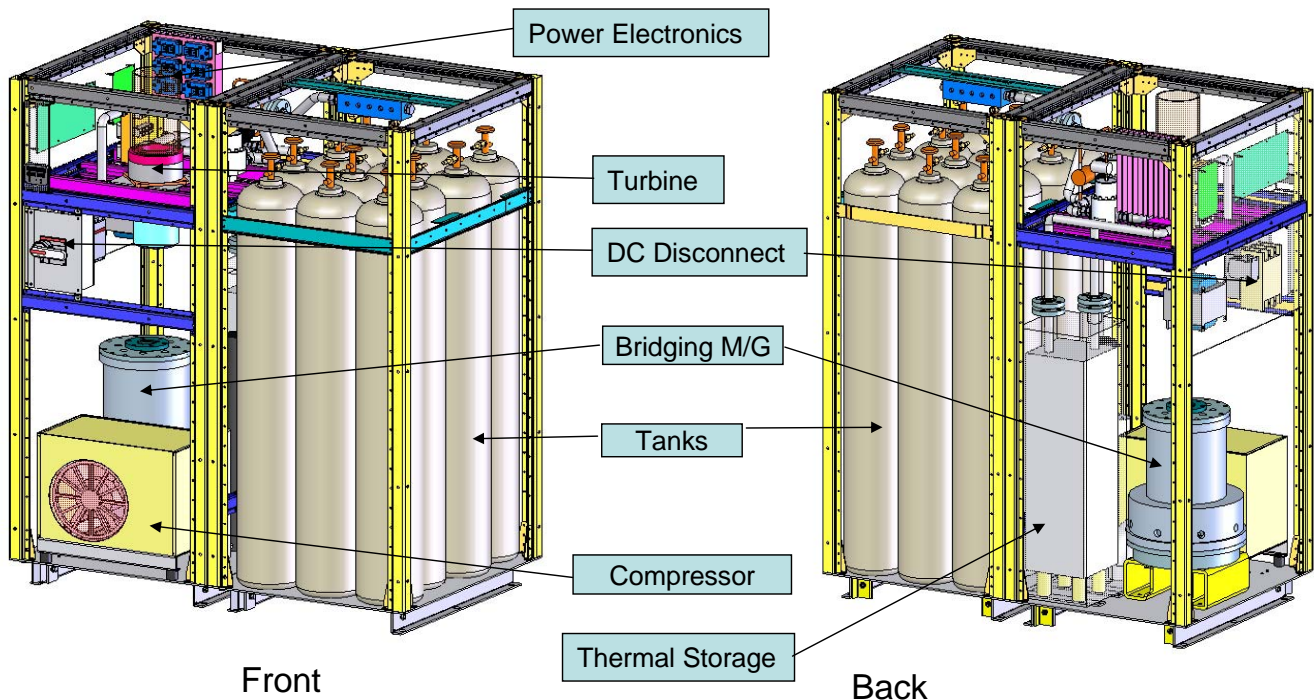


FIGURE 3
TACAS COMPONENT LAYOUT

configuration. This means that the base TACAS model should take the same DC input/output cabling as a battery cabinet, without any need for AC power.

What Should This Product Look Like?

The MRD called for TACAS to be packaged in standard-sized cabinets that would fit through typical doorways. Each cabinet will be 800 x 1000 x 1900mm (WxDxH).

The design engineers also chose to make TACAS a modular product with a minimum of two cabinets. The base cabinet would house the flywheel, air compressor, TSU, controls, power converters and the turbine/alternator assembly. The other cabinet(s) would house compressed-air cylinders and associated manifolds. Additional air-cylinder cabinets could be added to the two-cabinet minimum, either for extended runtimes or for effectively faster recharge times.

One of the design objectives is to make TACAS as compact as possible. In particular, the goal is to give a standard TACAS unit approximately the same footprint as a battery system with flooded jars. This might not be possible in all power ratings, but most configurations should be competitive in size.

What Should This Product Cost?

The development team's goal is to have the installed cost of TACAS be competitive with the installed cost of a quality system of flooded jars. Early indications are that production models will meet this cost target. Furthermore, the longevity and minimal maintenance requirements of the TACAS system should give it a lower life-cycle cost than either VRLA or flooded batteries.

DEVELOPMENT CHALLENGES

Optimizing the Expansion Turbine

The TACAS turbine presents some unusual choices to our engineering team. Unlike most other turbines, the expansion turbine has no combustion gases in the exhaust stream. The exhaust stream consists of clean air, accompanied by some amount of noise. Fortunately, the noise can be easily muffled to comfortable levels. The issue is what to do with the air itself.

The turbine efficiently extracts heat energy from the air stream, so that the exit air temperature is only a few degrees above room temperature. By the nature of our airflow control system, we can control the temperature of the exit air by adding more or less bypass (unheated) air through one of the flow valves. Since the unheated air is extremely cold, we could blend a small amount of bypass air into the exit air to produce exhaust air at 55° F – the same as the under-floor air in a raised-floor data center.

Although the TACAS airflow is fairly modest – about 700 cubic feet per minute per TACAS unit – some of our development engineers wondered if the cool air would be

helpful during the first two or three minutes of discharge, while the computer-room air conditioning system was rebooting and coming back online.

But while some engineers wanted to duct cool air into the computer room, others wanted to divert the slightly warm exit air into the tank cabinet(s). Since the air tanks will become cold during discharge, the warmer exit air would actually transfer a small amount of heat energy into the air tanks and allow a slightly longer discharge time. At this time, it appears that the warmer heads will prevail. Unblended exit air will either be ducted into the tank cabinets or vented into the surrounding room.

Compressor Issues

As mentioned earlier, compressors rated for 4500 PSI are widely available throughout the world. The trick is selecting an affordable compressor with the performance characteristics required for this type of product.

The team is running endurance tests on several commercial compressors, to see which will last longest with the least maintenance. When the endurance champs are determined, we will select one to be the standard compressor in the base product. The key selection criteria will be reliability and form factor. Cost will be considered, but only if one of the top candidates is significantly higher or lower than the others.

System Controls

With three different energy sources to manage, the controls will have an interesting balancing act during and after discharge events. The issue is the relatively slow dynamic response of the compressed-air and thermal energy sources.

During normal operation when the UPS has normal input power, the flywheel needs to be kept at full speed, ready to respond to short-term power demands. The compressed-air tanks need to be maintained at full capacity, and the TSU maintained at operating temperature.

When the DC bus voltage dips, indicating that the UPS has lost input power, the controls must monitor the flywheel rotational speed to determine when (and if) the air valves should be opened for a regular discharge. While the air tanks are discharging through the TSU, the system controls must restore the flywheel rotational energy to some amount less than 100%. The flywheel must have most of its energy available for momentary step loads but it must also be available to store excess energy from a step unload event, during the time required for the flow valves to respond appropriately.

Fortunately, our design team has experience with both flywheel controls and process-control airflow management. The control scheme is sophisticated, but

easily managed with the board-level computer technology available today.

Air Cylinders

Compressed-air storage is a mature technology, and our engineers can choose from a wide assortment of air cylinders and pressure vessels systems worldwide. All will provide satisfactory performance.

Unfortunately, there will not be a single, universal system that can be applied globally. Different regions of the United States have different regulatory requirements; some will accept DOT gas cylinders while others require ASME-code pressure vessels. Vessels conforming to the EU Pressure Equipment Directive will be required in Europe. Similarly, Japan has its own pressure vessel regulations.

In all probability, we will source cylinders for international sites from their respective countries. For domestic customers, we will create distribution agreements with local equipment-leasing companies in various regions. The leasing companies would provide both the tanks and the periodic inspections required by their local authorities.

NON-TECHNICAL CHALLENGES

While significant technical milestones must be achieved by the engineering team, some of the biggest remaining challenges cannot be solved in the R&D lab. These other challenges are looming because of human nature and the newness of the TACAS product.

First, TACAS must find its place in the minds and hearts of the local building inspectors. The entire assembly will be UL listed, but there may be questions about which building codes are applicable to the product. The installation will require connecting the air manifolds between the power cabinet and the air tank cabinet, so regulations concerning high-pressure air will be in play. In addition, TACAS will be used with UPS equipment, so typical power system regulations will apply.

Second, in some communities there will be two different trade unions involved: those making the air-manifold connections and those making the electrical connections. We plan to contact different regional trade unions to persuade them to resolve these issues in advance of product launch.

Third, the unorthodox nature of the product will cause many customers to wonder, "Can that thing work?" It will require much patience and many educational articles in the trade press to fully convey the story.

DEVELOPMENT TIMETABLE

Early prototype systems have successfully achieved backup times of 15 minutes at 80 kW. The next prototypes will test optimized system components and verify the controls design during the third quarter of 2004. Alpha units should begin shipping in late 2004, with Beta units shipping in early 2005. If all goes well, commercial production can begin in Q3-05.

CONCLUSION

Since TACAS is based upon several mature technologies, it is expected to meet all its performance goals. If it can achieve its cost targets, it should also be a commercial success.

AUTHOR'S BIO:

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 19 years of power systems experience also includes applications engineering and marketing for photovoltaic systems and switching power supplies.