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**CRADA FINAL REPORT
FOR
CRADA NUMBER ORNL98-0521**

**DEVELOPMENT OF
AN ELECTRIC BUS INVERTER
BASED ON ORNL
AUXILIARY RESONANT TANK (ART)
SOFT-SWITCHING TECHNOLOGY**

**Curt Ayers
Oak Ridge National Laboratory**

**John Powell
Electric Transit Vehicle Institute**

**Ron Sweeney
Chattanooga Area Regional Transit Authority**

**Joe Ferguson
Advanced Vehicle Systems**

**Prepared by the
Oak Ridge National Laboratory
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Engineering Technology Division

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ABSTRACT

The Power Electronics and Electric Machinery Research Center (PEEMRC) of Oak Ridge National Laboratory (ORNL) has for many years been developing technologies for power converters for motor drives and many other applications. Some of the research goals are to improve efficiency and reduce audible and electromagnetic interference noise generation for inverters and the driven loads. The converters are being required to produce more power with reduced weight and volume, which requires improvements in heat removal from the electronics, as well as improved circuit designs that have fewer electrical losses. PEEMRC has recently developed and patented a soft-switching inverter topology called an Auxiliary Resonant Tank (ART), and this design has been tested and proven at ORNL using a 10-kW laboratory prototype.

The objective of this project was to develop, test, and install the ART inverter technology in an electric transit bus with the final goal of evaluating performance of the ORNL inverter under field conditions in a vehicle. A scaled-up inverter with the capacity to drive a 22-ft bus was built based on the 10-kW ORNL laboratory prototype ART soft-switching inverter. Most (if not all) commercially available inverters for traction drive and other applications use hard-switching inverters.

A Cooperative Research and Development Agreement was established with the Chattanooga Area Regional Transit Authority (CARTA), the Electric Transit Vehicle Institute (ETVI), and Advanced Vehicle Systems (AVS), all of Chattanooga, along with ORNL. CARTA, which maintains and operates the public transit system in Chattanooga, provided an area for testing the vehicle alongside other similar vehicles in the normal operating environment. ETVI offers capabilities in standardized testing and reporting and also provides exposure in the electric transit vehicle arena for ORNL's technologies. The third Chattanooga partner, (AVS) manufactures all-electric and hybrid electric transit buses using inverter drive systems from several manufacturers. AVS provided help in field installation, and parts for laboratory testing.

A 100-kW field-ready unit was developed, tested in an ORNL laboratory, and installed and successfully operated in a CARTA bus in Chattanooga. The tests on the vehicle were performed at a CARTA maintenance facility and at a 1-mile test track in Chattanooga managed by CARTA.

INTRODUCTION

The Power Electronics and Electric Machinery Research Center at the Oak Ridge National Laboratory (ORNL) has been involved in the development of power electronics for various applications for many years. A recent development in the laboratory involved an Auxiliary Resonant Tank (ART) soft-switching technique, and a 10-kW three-phase unit was built to demonstrate the functionality of the design. This circuit was developed with reliability and cost in mind by minimizing component count and using a design that allows for minimum stress on the electronic components. The soft-switching also provides for lower electromagnetic interference (EMI) emissions from the power switches.

The ART inverter lends itself to three-phase power for electric motor traction drives in automotive and other applications. This project was initiated to allow this new inverter technology to be developed and tested directly in an electric vehicle operating on a city bus route.

OBJECTIVES

A Cooperative Research and Development Agreement (CRADA) was established with the Chattanooga Area Regional Transit Authority (CARTA), the Electric Transit Vehicle Institute (ETVI), and Advanced Vehicle Systems (AVS), all of Chattanooga, Tennessee, along with ORNL. The goals of this CRADA include reengineering the 10-kW prototype inverter to full-scale size, developing motor control methods, installing and testing it in a real-world situation, and evaluating performance improvements that can be made by applying the soft-switching methods in the commercial arena.

The final results from this CRADA are included in a report documenting the performance of the inverter in the laboratory and in the vehicle. These results can provide a basis for licensing of this technology to parties interested in commercial uses for the electric vehicle and other industries.

BENEFITS TO DOE SPONSOR OFFICE

The ART technology was developed at ORNL and sponsored by the Department of Energy (DOE). This project provides an avenue to directly apply the technology in the field in a rapid fashion, allowing the invention to be evaluated in a real-world situation – on a vehicle. Availability of this type of data early in the development of any technology promotes rapid commercialization of DOE laboratory innovations. Evaluation of such project successes aids DOE and its laboratories to direct funding to the most appropriate areas for future development of the most promising technologies. Furthermore, the experience of in-vehicle testing by lab staff is valuable in helping the researchers better understand application issues.

TECHNICAL DISCUSSION OF WORK

To begin design by scaling up the original ART prototype (10-kW), the size of the new inverter had to be determined. Before the CRADA team was able to select the vehicle, it was decided that a 100 kW inverter would cover the range of possible choices, and design proceeded on this basis.

The first 100-kW unit (shown in Fig. 1) was designed and built at ORNL as a laboratory test unit to aid in finalizing the design. This unit was tested using an inductive load for debugging and functional testing, and was generally found to function well. Some aspects of the design/layout of components were noted for improvement in the final unit. After that phase was completed, the laboratory evaluation required running a typical electric bus motor to complete development of the controls, logic interfaces, etc. AVS provided a motor and accessories for the test stand to allow testing of the new inverter using a bus motor identical to the one that would be driven in the field.

Fig. 1. ORNL's first 100 kW ART prototype.

AVS also provided documentation on wiring and logic interfaces with the existing electronics on the traction drive system to allow the required interface from the new inverter to be designed. Due to the limited information available on the existing interfaces of the bus, the controller, the inverter, and the motor, this design required considerable effort to resolve.

One of CARTA's roles was to provide a vehicle from its operating fleet. This same vehicle was "borrowed" several times during the initial field tests (in the Chattanooga area) for the electronics and inverter and was used extensively at the Chattanooga TVA test track managed by CARTA. CARTA also provided shop support and drivers for the buses when necessary during the numerous tests and shared its experience with existing vehicle problems associated with the commercial inverters presently being used. ETVI has provided coordination support of the tests and technical help with documentation, drawings, and vehicle details. CARTA also provided the help needed in field tests, including operation and coordination of the test track evaluations.

Laboratory testing for the inverter was done under all load conditions (0-100%) with a reactive load and under partial loading (0-15%) when connected to the test motor on the test stand. Figure 2 shows our initial laboratory testing setup.

Fig. 2. ORNL test stand, ART inverter (foreground), and bus motor (behind).

Due to capacity of the laboratory direct current (dc) power supply current, full load condition was not achievable when mechanically loaded. The laboratory test stand consisted of an alternating current (ac) induction motor (identical to the type on the shuttle buses in Chattanooga), a load cell for measuring torque and speed, and a flat cogged-belt speed increaser arrangement; all were connected to a 600-hp water brake dynamometer. This test setup was used to run the motor through all speed conditions, although all loading conditions could not be simulated. Later in the lab testing, a friction brake was fabricated to simulate "off the curb" starting friction and inertial load. This allowed some necessary modifications to the torque algorithms for the motor controller, which improved the vehicle operation of the inverter/motor (further discussion below).

Fig. 3. Comparison of ORNL ART and conventional inverters.

Data taken during dynamometer tests (shown in Fig. 3) show the inverter efficiency to be 95–98% at low loads (in the 0–15% load range, dynamometer tests) and over 98% at full load (inductive load tests). This can be compared to the efficiency of a standard hard-switched inverter, which drops off rapidly at low loads; it is represented in Fig. 3 with data from a 10-kW hard-switched commercial inverter. At low loads the switching losses become a significant percentage of the load, which lowers the efficiency. The important thing to note is the flat profile of the ART efficiency curve over the entire load range. A dashed line at 97% indicates the goal for the year 2004 set by the Partnership for a New Generation of Vehicles (PNGV). The 1999 ORNL soft-switching inverter essentially meets this 2004 goal.

Conventional inverters create a large amount of switching noise in the dc link current due to the on/off switching transients as can be seen in Fig. 4. The current can be seen to switch on from full and fractional currents and back to zero continuously in this example.

Fig. 4. Voltage and current waveforms for a hard-switched inverter.

The ART inverter topology allows a much smoother dc current waveform due to the improved switching scheme, as shown in Fig. 5.

Fig. 5. Voltage and current waveforms for ORNL's ART inverter.

The ART inverter controller was designed to be switchable from soft- to hard-switching for testing and comparison purposes. An approximate 2-hour test was run with the unit switched over in the middle of the run to allow comparison of efficiencies of the two conditions. Data presented in Fig. 6 show the inverter efficiency during the two conditions, and also the overall system efficiencies during the two conditions.

Fig. 6. Efficiency comparison between soft- and hard-switched mode.

When comparing the efficiencies of the two *inverters* between soft- and hard-switching, no significant difference is noted. The overall system efficiency, however, shows a significant drop in efficiency when the control is changed to hard switching. It is suggested that this drop in efficiency is caused by increased motor core losses and resistive losses in the motor windings and power cabling due to the noisier hard-switching method.

During the laboratory tests, including endurance tests up to 2 h at 15% load, the inverter ran cool with minimal water flow through the internal heat exchanger (<0.5 L/min). The inverter was run-tested at 100% load with an inductive load for 3-4 h for initial trials and then used to drive the motor on the test stand through various tests for more than 20 h total time.

After an initial field trial to verify interfaces, some minor problems were resolved in the lab, and the unit was returned to the field to begin tests in the vehicle. As compared to the ORNL test stand, a significant difference in load dynamics was discovered; the existing control algorithm could not handle this load. The control methods had to be

altered to accommodate loads seen in the vehicle that were not anticipated during laboratory tests. The primary challenge was seen to be control of accelerating and braking against the large inertia of the electric bus, such as the acceleration/deceleration loading when moving at slow speeds over a speed bump.

The motor control scheme utilized on this project is a method of *self-sensing* for motor speed. This method was applied early in the development and has been highly successful in all laboratory testing. The motor that was available for testing had no speed sensor, and the flux sensors that are imbedded in the windings were faulty. This encouraged the use of the self-sensing technique, which requires no speed or position sensors for the motor. Self-sensing is seen as highly advantageous in the electric vehicle industry due to simplification of the motor drive (by reduction of sensors) and thus increased reliability and reduced cost of the motor drive system. When the self-sensing algorithm was incorporated in the inverter drive early in the laboratory testing, its performance was excellent, leading us to incorporate this unplanned improvement. This decision proved positive during all of the laboratory work, such as final development of the inverter and adjustments, and in driving the bus motor on the test stand. The existing vehicle motor and inverter uses two flux sensors and a speed encoder, which are not required when using the ORNL self-sensing scheme. When the inverter was installed in the field and logic interfacing completed, some of the differences in the test stand motor operation and the field situation (such as vehicle inertia) created the need for modifications to the self-sensing software. It was also determined that there was significantly more EMI in the actual vehicle due to existing vehicle electronics than that which was experienced in the laboratory. Modifications were made to harden the inverter to EMI susceptibility, allowing the bus to function well for the test track operations, and the team was able to collect preliminary field data.

Data were collected at the Chattanooga test track during driving cycles and steady state driving. The driving cycles (Fig. 7) consisted of vehicle startup, maximum acceleration to 27 mph, then deceleration to a full stop using only regenerative braking. The steady state data (Fig. 8) were collected for several miles around the test track running at approximately 27 mph. Both the driving cycles and the steady state trials were done for comparison to data to be collected from the standard commercial inverter drive while powering the same vehicle.

It was also intended to collect data on the actual bus route in the Chattanooga downtown area in addition to the test track data. Calendar and budget constraints precluded the team from acquiring these additional data, and also from reinstalling and gathering data on the existing commercial inverter.

Fig. 7. Comparison of ORNL driving cycle to previous ETVI driving cycle.

Fig. 8. ORNL ART self-sensing inverter in electric bus steady state 27-mph test track trials.

Preliminary data acquisition with the ORNL ART inverter powering the electric bus was completed without the use of an online data acquisition system, which became unavailable during the time that was required to finish up the field-work. We were unable to acquire all the data that would have been desired using an online system as well as data on the standard commercial inverter in the bus. The data taken by ORNL relied on other instrumentation used for vehicle/battery operation. The data format was

sufficiently different such that comparison to older data is difficult, so only some simple comparisons were made to previous data from the standard inverter. Figure 9 shows some older data taken by ETVI on the commercial inverter, previous to ORNL field tests. Notice in the amp-hour discharging data for both inverters that the ART inverter uses about 1.1 A-h/min (average battery voltage 295 V) powering the vehicle at 27 mph. The commercial inverter data (previous trials on a different project, same vehicle) shows a discharge rate of 1.1 A-h/min with the average battery voltage much higher (328 V), using energy at a rate of about 20 kW. This is about an 11% increase in energy rate over the ORNL ART inverter.

Fig. 9. Standard commercial inverter data (ETVI) showing vehicle speed, battery voltage, and A-h.

The team hoped to leave the final inverter on the vehicle to allow future testing and use along its normal city routes. While the inverter was made to function very well for the test track tests, there were still nuisance circuit trips due to control problems with the heavy vehicle and also due to strong EMI found in the electric bus from preexisting commercial electronics. The inverter needs to be further hardened to EMI to bring the self-sensing controls to a "commercially acceptable" level and a position where we could allow the vehicle to operate in the public domain. The power transistor manufacturer has released a new version of the insulated gate bipolar transistor (IGBT) used in the ORNL ART inverter that solved what they called "unwanted operation", which was very closely related to the problems experienced during field operation. This new IGBT was designed in a different sized package and was unusable in the scope of this project as a replacement (without significant mechanical changes), but it should be changed to improve the inverter hardening against EMI.

DESIGN PHILOSOPHY AND PERFORMANCE GOALS

The PNGV has set goals for performance of automotive electric motors and power inverters and environmental conditions in which they must operate. The scaled-up ART design used these goals as a basis for scaling up the ORNL ART prototype from 10 to 100 kW. The 1998 ORNL design met the year 2000 goal of 4 kW/kg, with an estimated cost (mass production, using existing electronics technology) of approximately \$20/kW. Although these were not the main goals of the project, they were used as guides for the design process for the new inverter topology.

PLANS FOR FUTURE WORK

With further funding, it is intended to complete the tuning of the self-sensing algorithm to overcome the problems experienced in the heavy vehicle, and further evaluate and remove the noise-related circuit trips seen when the inverter is installed in the electric bus. Present sensitivity to the EMI in the vehicle could be further reduced by replacement of the existing obsolete power transistors with the later corrected model.

More extensive data could be acquired on the soft-switching inverter in the field for comparison to the laboratory data, and the comparison data from the existing commercial inverter could be collected and compared to the ORNL unit under various driving conditions.

An AVS engineer mentioned early in the project that it would be helpful to see the inverter (and controls) evaluated driving a commercial off-the-shelf motor. Their interest is in being able to utilize a readily available lower-cost motor, and one that could possibly be manufactured in the Chattanooga area. The existing motor on the vehicle under test was an oil-cooled motor that used two flux sensors and a speed encoder, sensors that the ORNL inverter controller would not need. This project paves the way for testing with a commercial off-the-shelf induction motor with the ORNL ART inverter.

The partners have also expressed interest in seeing this inverter technology commercialized in their region. This business would fit in well with the electric vehicle industry that is rapidly growing in the Chattanooga area.

CONCLUSIONS

The ORNL ART inverter performed well as a soft-switching inverter both in the laboratory and in the field installation in the electric transit bus. The efficiency of the inverter was shown from laboratory testing to be in excess of 95% at low and high load conditions, an improvement over hard-switching inverters that exhibit significantly decreased efficiency as the load drops from full load.

In scaling up the 10-kW prototype to the first 100-kW unit, lessons were learned about the geometry of the new inverter. This new 100-kW unit, though, had only about twice

the volume of the original 10-kW prototype. The final 100-kW unit developed for installation in the electric bus had slight changes in geometry to overcome the problems in the first unit, but with no significant increase in volume (size represented in Fig. 10 below).

Fig. 10. Approximate size of 100-kW ORNL ART inverter.

This second unit has performed very well, running very cool at full power with minimal cooling water. It was tested completely sealed in the NEMA 12 field enclosure in the laboratory and in the actual vehicle. Embedded temperature sensors in the box and electronics indicated acceptable temperature levels throughout the lab testing and August 1999 field testing at the test track in Chattanooga.

The final inverter design compared well to the PNGV goals for automotive industry power inverters. The ORNL 100-kW ART inverter came very close to the *power density* goal, calculated at about 8 kW/L. Although the *specific cost* for the ORNL inverter was high, this is mostly due to present commercially available power electronics prices. The estimate for ORNL ART in mass production is about \$20/kW. This number will come down when state-of-the-art power electronics come to market with the combined effect of mass production quantities for those electronics. The *specific power* of the ORNL ART inverter (4 kW/kg) exceeded the PNGV goal.

Development and use of the ORNL self-sensing technique (removing the need for magnetic flux signals and speed encoding) was a great success in the laboratory testing, and even with a few challenges during installation, the self-sensing was highly successful in the field tests as well.

Fig. 11. ART bus inverter installation and testing work at CARTA maintenance facility, Chattanooga.

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