OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2010/127
C/ORNL00-0584

CRADA FINAL REPORT
for
CRADA Number ORNL00-0584 with
General Motors Advanced Technology Vehicles

Advanced Accessory Power Supply Topologies

Principal Investigator: L. D. Marlino

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Final Report for CRADA ORNL00-0584

Advanced Accessory Power Supply Topologies

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Prepared by the
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I. ABSTRACT

This Cooperative Research and Development Agreement (CRADA) began December 8, 2000 and ended September 30, 2009. The total funding provided by the Participant (General Motors Advanced Technology Vehicles [GM]) during the course of the CRADA totaled $1.2M enabling the Contractor (UT-Battelle, LLC [Oak Ridge National Laboratory, a.k.a. ORNL]) to contribute significantly to the joint project. The initial task was to work with GM on the feasibility of developing their conceptual approach of modifying major components of the existing traction inverter/drive to develop low cost, robust, accessory power. Two alternate methods for implementation were suggested by ORNL and both were proven successful through simulations and then extensive testing of prototypes designed and fabricated during the project. This validated the GM overall concept. Moreover, three joint U.S. patents were issued and subsequently licensed by GM.

After successfully fulfilling the initial objective, the direction and duration of the CRADA was modified and GM provided funding for two additional tasks. The first new task was to provide the basic development for implementing a cascaded inverter technology into hybrid vehicles (including plug-in hybrid, fuel cell, and electric). The second new task was to continue the basic development for implementing inverter and converter topologies and new technology assessments for hybrid vehicle applications. Additionally, this task was to address the use of high temperature components in drive systems.

Under this CRADA, ORNL conducted further research based on GM's idea of using the motor magnetic core and windings to produce bidirectional accessory power supply that is non-galvanically coupled to the terminals of the high voltage dc-link battery of hybrid vehicles. In order not to interfere with the motor's torque, ORNL suggested to use the zero-sequence, high-frequency harmonics carried by the main fundamental motor current for producing the accessory power. Two studies were conducted at ORNL. One was to put an additional winding in the motor slots to magnetically link with the high frequency of the controllable zero-sequence stator currents that do not produce any zero-sequence harmonic torques. The second approach was to utilize the corners of the square stator punching for the high-frequency transformers of the dc/dc inverter. Both approaches were successful. This CRADA validated the feasibility of GM's desire to use the motor's magnetic core and windings to produce bidirectional accessory power supply.

Three joint U.S. patents with GM were issued to ORNL and GM by the U.S. Patent Office for the research results produced by this CRADA.

II. STATEMENT OF OBJECTIVES

Electric vehicles, hybrid (including plug-in hybrid) vehicles, and fuel cell powered vehicles will likely have a low voltage (12V or 42V) battery to operate accessory loads such as radios, lights, instruments, etc. These loads can range from 1–4 kW. Standard automotive alternators are not easily adapted to these alternative vehicles, so the practice to date was to use dc/dc converters to charge the accessory battery from the high voltage battery pack. At the beginning of the CRADA, dc/dc converters could be designed to achieve very high power density (>50W/cu. in.)

and excellent efficiency (>90%) but were very complex, not highly reliable, lacked surge capacity, and were expensive.

This CRADA investigated potential solutions for providing accessory power in hybrid vehicles. The primary objective was to reduce cost and increase reliability of current day solutions.

Further work provided the basic development for implementing a cascaded inverter technology into hybrid vehicles for the purpose of eliminating bulky magnetic components normally associated with the use of multiple converters drawing energy from two different energy or storage sources.

The next task was to continue the basic development for implementing inverter and converter topologies and new technology assessments for hybrid vehicle applications. Additionally, this task was to address the use of high temperature components in drive systems.

III. BENEFITS TO FUNDING DOE OFFICE'S MISSION

The CRADA supported the DOE Energy Efficiency and Renewable Energy's Office of Advanced Automotive Technologies (OAAT) – now the Office of Vehicle Technologies – programs to develop fuel-efficient, environmentally friendly passenger vehicles. Successful completion directly addressed the technical barriers of the OAAT's Power Electronics & Electric Machinery research and development (R&D) plan.

DOE did not directly contribute funding to this CRADA, but the work obviously depended on the use of laboratories, equipment, and research staff expertise that had been established by the Vehicle Technologies Program.

IV. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

Hybrid vehicles will likely have a low voltage (12V or 42V) battery to operate accessory loads such as radios, lights, instruments, etc. These loads can range from 1–4 kW. Standard automotive alternators are not easily adapted to these alternative vehicles, so the practice was is to use dc/dc converters to charge the accessory battery from the high voltage battery pack. At the beginning of the CRADA, dc/dc converters could be designed to achieve very high power density (>50W/cu. in.) and excellent efficiency (>90%), but were very complex, not highly reliable, lacked surge capacity, and were expensive.

The initial task of this CRADA was to determine the feasibility of modifying major components of the existing traction inverter/drive to develop low cost, robust, accessory power. GM presented ORNL with their concept which had already been studied in some detail and engaged ORNL in further research with the concept. ORNL explored the feasibility of GM's concept and other alternatives that might be found to be beneficial to a successful outcome. GM provided data for the inverter, motor, and batteries. A basic specification for the accessory power function was also provided by GM. Simulations were performed over the full operating range to determine if acceptable performance was feasible and if motor performance was affected. A trade-off study of ideas was also conducted. As a result of this effort, ORNL suggested two alternate approaches.

In order not to interfere with the motor's torque and to reduce the number of high-current switching components, ORNL suggested using zero-sequence, high-frequency harmonics carried by the main fundamental motor current for producing the accessory power. The approach was to put an additional winding in the motor slots to magnetically link with the high frequency of the controllable zero-sequence stator currents that do not produce harmonic torque. After the simulations gave promise that the concept would work, ORNL built a prototype system using GM-furnished drive components and collected and analyzed data over the operating conditions

Figure 1 shows the prototype motor with this arrangement which was rewound from an existing GM motor with additional winding in the motor slots for the accessory power production. Figure 2 shows the water-ethylene glycol cooling loop of the prototype motor.

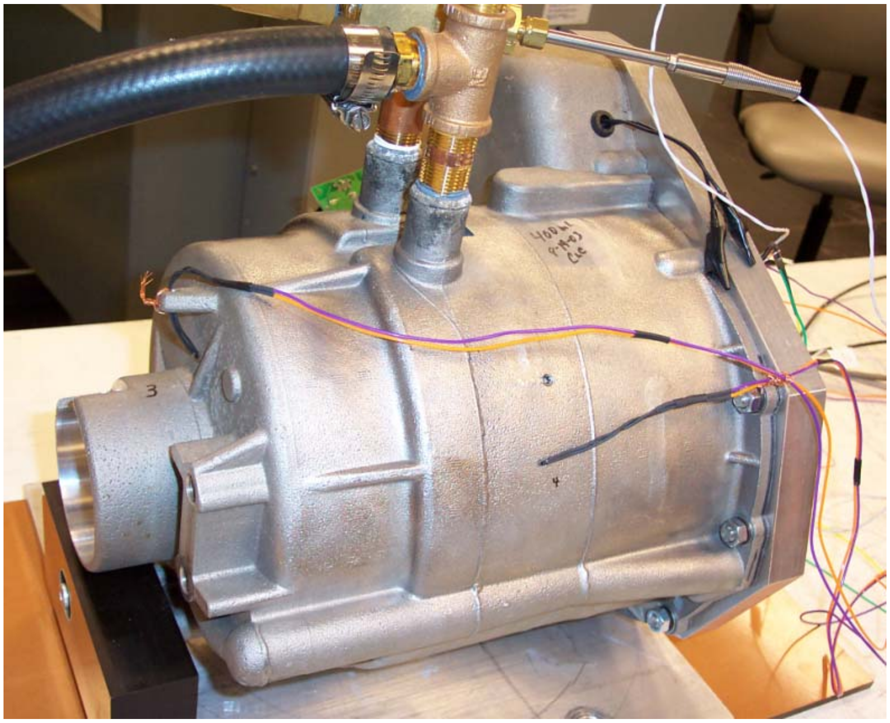

Fig. 1. A rewound GM motor with additional winding in the motor slots for accessory power production.

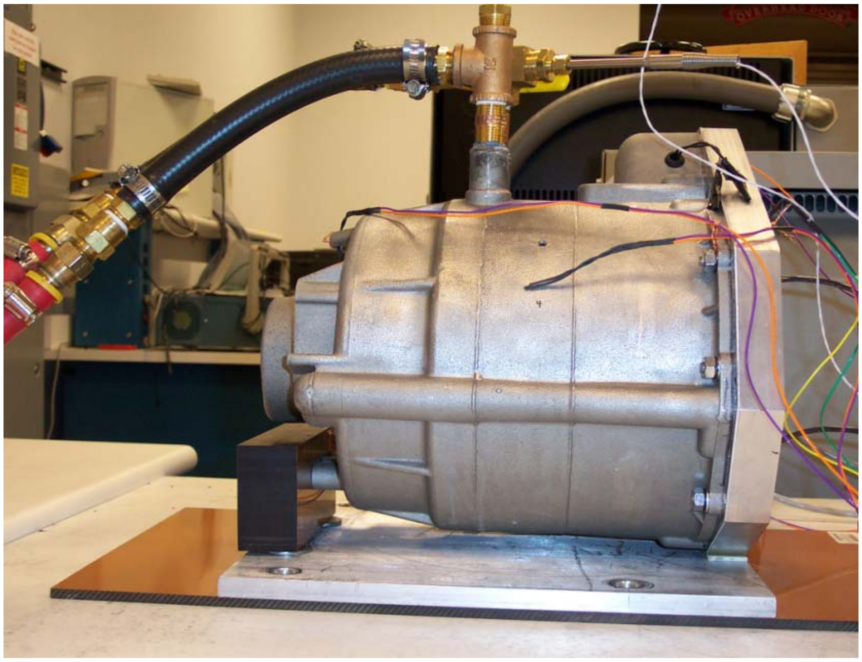

Fig. 2. Water-ethylene glycol cooling loop of the prototype motor.

The second method was to utilize the transformer approach and subsequently to use the corners of the square stator punching for the high-frequency transformers of the dc/dc inverter. The first prototype that combined the motor and transformer together with an additional fourth leg of the inverter showed the validity of the zero-sequence concept. We learned from the first prototype that the efficiency needs to be improved and that galvanic isolation must be incorporated.

In order to obtain the 12V and 42V accessory power from a 325V dc bus, the following conventional approach shown in Fig. 3 might be used.

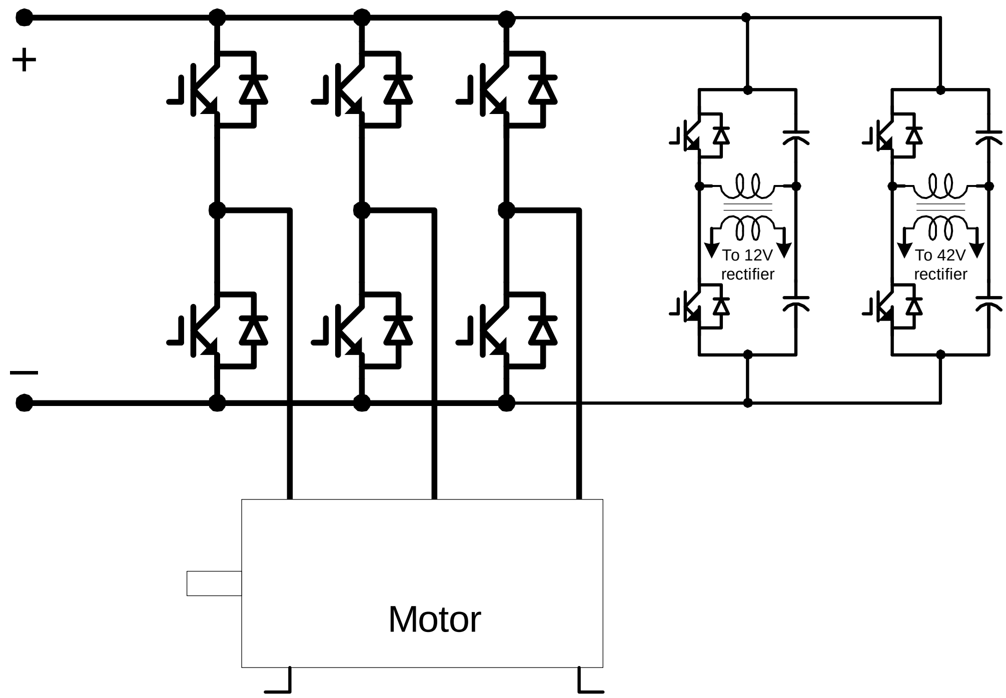

Fig. 3. A conventional approach of two additional half-bridges for 12V and 42V accessory power supplies.

The two additional half-bridges provide the adjustable outputs for the 12V and 42V supplies, respectively. This conventional circuit has nothing to do with the zero sequence and it is totally independent from the three-phase inverter operation. The only drawback is that the additional insulated gate bipolar transistors (IGBTs) increase the cost.

In order to reduce the required number of IGBTs for the accessory power supply, a new circuit was conceived. The circuit uses only one IGBT for each accessory voltage supply. A resonant operation is induced to provide a higher-magnitude sine wave for increasing the power handling capability of the transformer. Figure 4 shows the circuit.

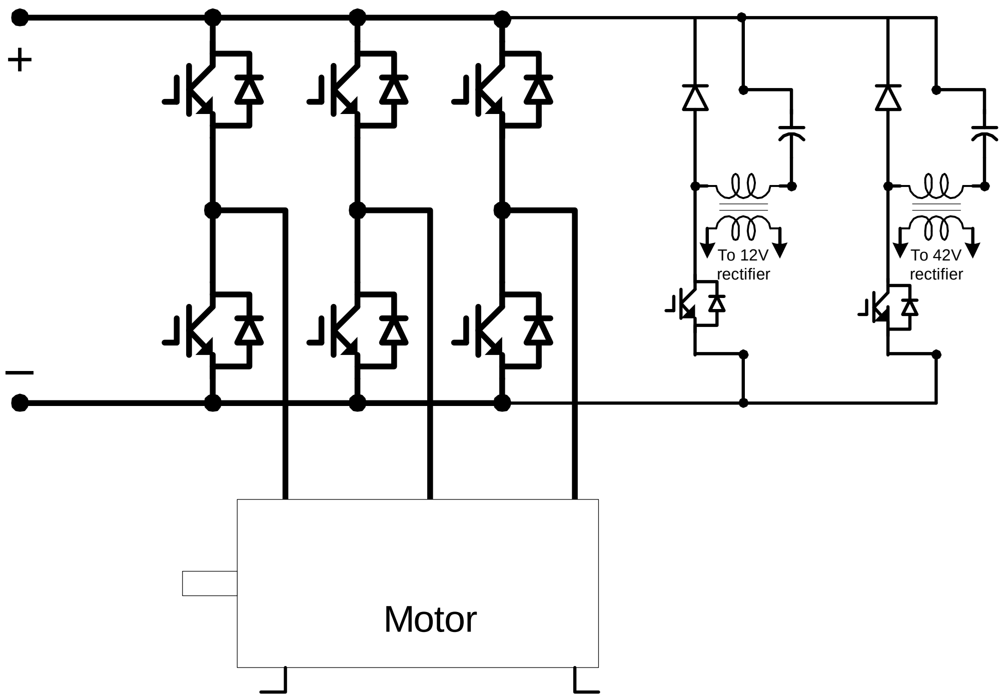

Fig. 4. Zero sequence resonant converter and three-phase inverter circuit.

Because the circuit utilizes the switching of the main IGBTs of the three-phase inverter, a reduction in the number of components becomes possible. The test results and efficiencies of individual stages calculated from the test data showed that average efficiencies of the operating region for the high voltage to 12V accessory power production is 0.91 for the high-voltage rectifier and IGBT stage, 0.85 for the transformer and capacitor stage, and 0.70 for the low-voltage rectifier stage. Efficiency improvement can be addressed for the targeted stage. For example, lower conduction loss diodes may be used for improving the efficiency of the low voltage rectifier stage.

Figure 5 shows the second (transformer) approach prototype motor with square stator core. Figure 6 shows the four corners of the square stator core which are used for the accessory power transformers. Figure 7 shows the primary coil and secondary coil of one phase of a three-phase accessory power conversion system that utilizes the corners of the stator laminations. Figure 8 shows the front view of the prototype motor of the second approach with a shaft guard in place for safety. Figure 9 shows the prototype motor mounted on the test bed for obtaining test data. Figure 10 shows the accessory power test layout of the prototype motor utilizing corners of square stator laminations.

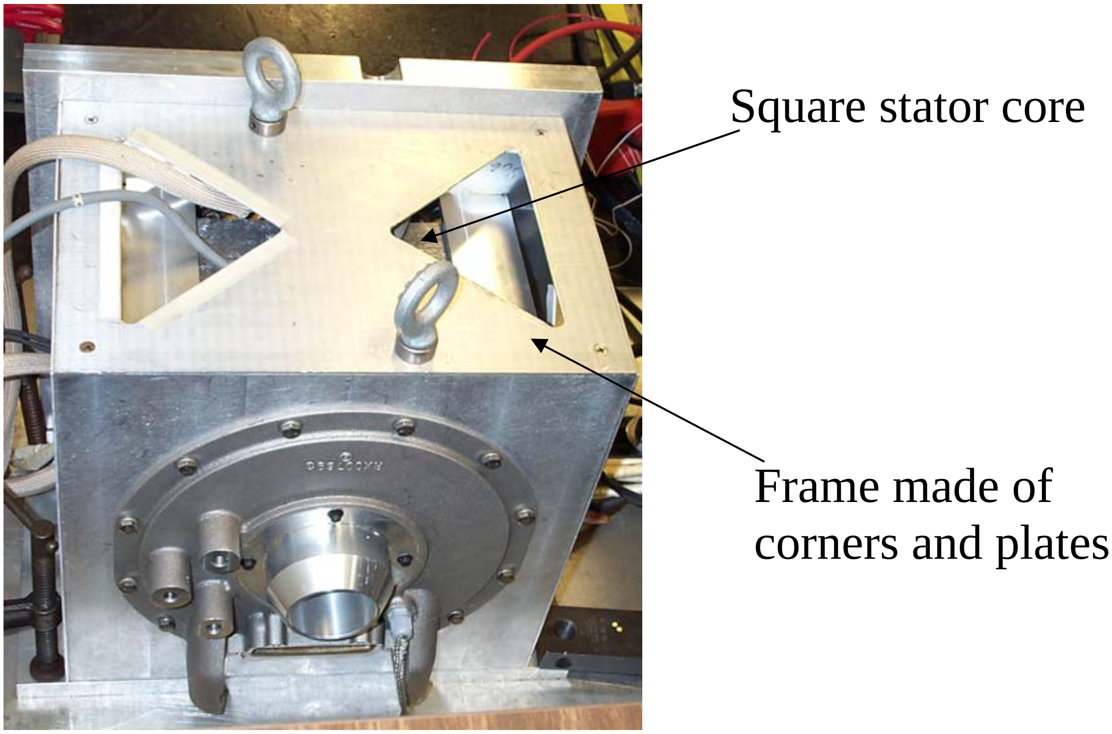

Fig. 5. Second approach of prototype motor with square stator core.

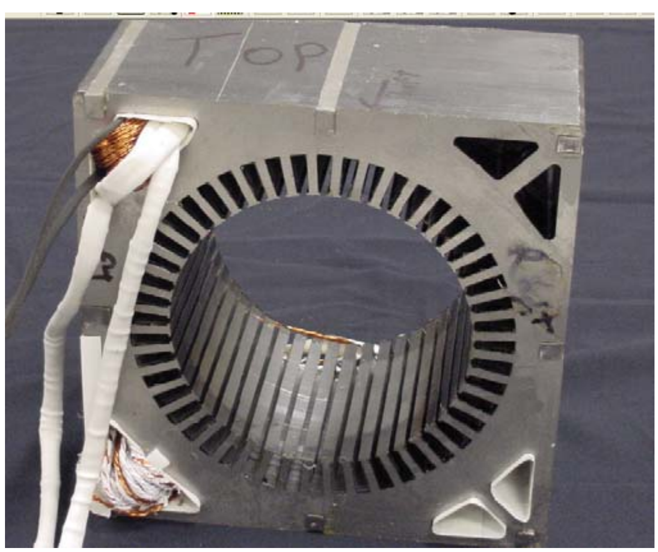

Fig. 6. Four corners of the square stator core used for accessory power transformers.

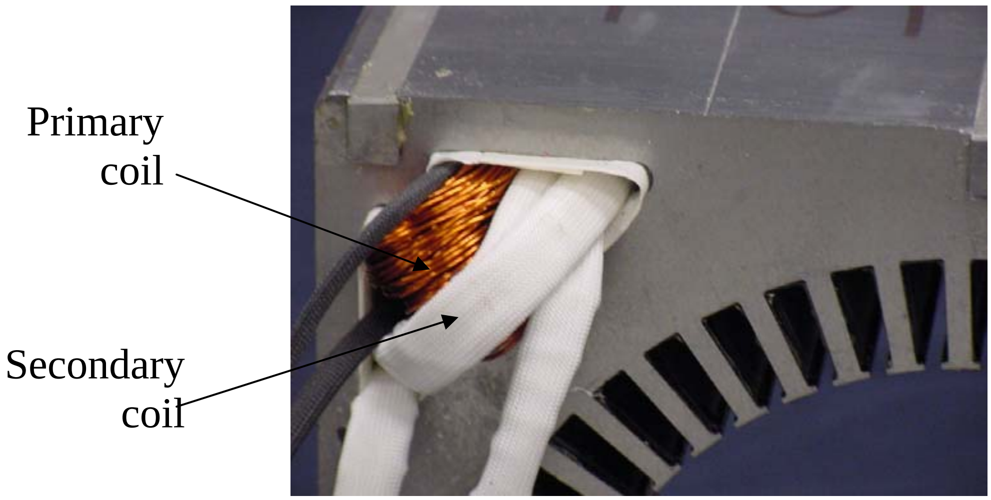

Fig. 7. One phase of three phases.

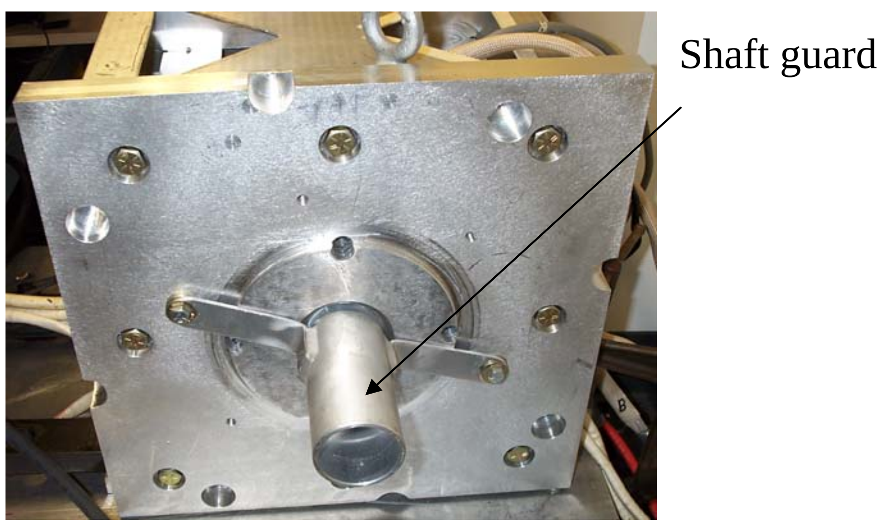

Fig. 8. Front view of prototype motor.

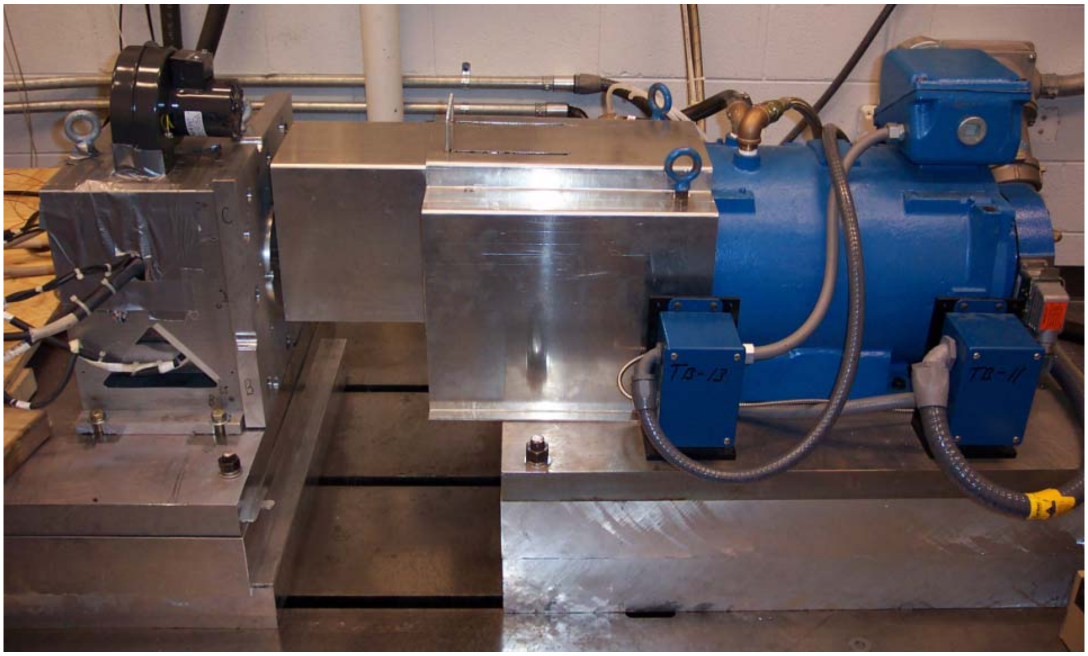

Fig. 9. Square stator core prototype motor mounted on test bed.

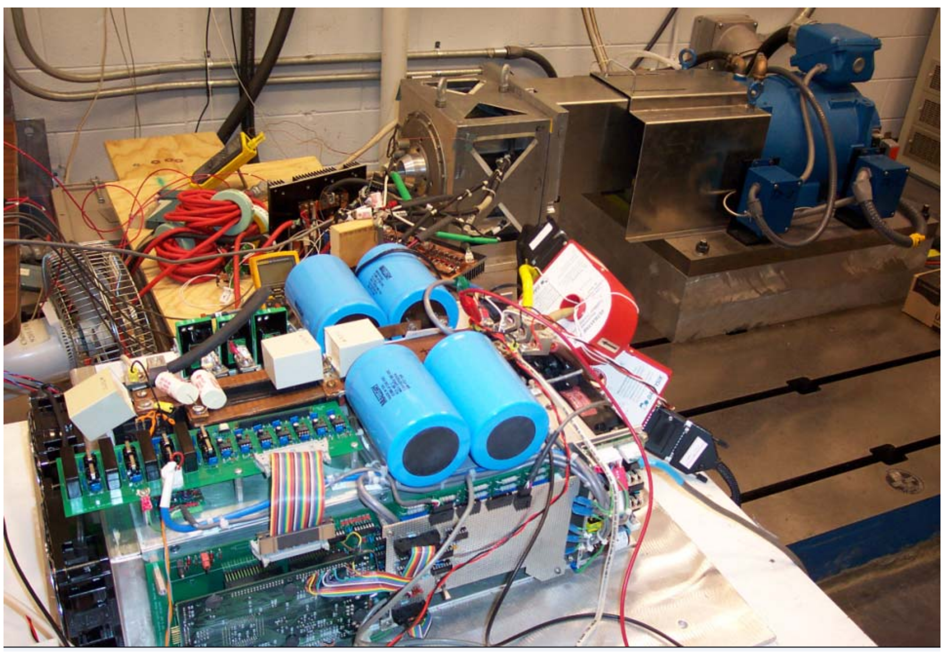

Fig. 10. Accessory power test of prototype utilizing corners of square stator laminations.

Both the additional secondary winding in the motor slots of the first approach and the transformer approach were successfully validated by extensive test data. These prototype developments and evaluations confirmed the feasibility of GM's desire to use the motor's magnetic core and windings to produce bidirectional accessory power supply. This research also points out that efficiency can be improved by using lower loss core materials and to provide more room for the additional secondary windings by using the corners of the stator punchings for reducing the iron and copper losses.

The next phase of the project addressed the basic development for implementing a cascaded inverter technology into hybrid vehicles for the purpose of eliminating bulky magnetic components normally associated with the use of multiple converters drawing energy from two different energy or storage sources. GM had already done considerable work with this concept. Motors and controllers were provided to ORNL for further R&D. As the research progressed, numerous problems developed in the use of the existing controller used to operate the system. Researchers concentrated on resolving these issues, which were found to be extremely difficult to trace, consistently reproduce, and remedy. Several visits back and forth by researchers were made in an effort to resolve all of the issues. Progress was made, but the use for such a concept diminished as the overall vehicle architecture evolved with time. Significant changes were made by the auto industry and the government in an effort to address the needs of the world market and the events that influenced them over time.

Subsequently, direction was altered to perform more technology assessments for hybrid vehicle applications, and basic development continued for implementing inverter and converter topologies. The use of high temperature components in drive systems became of more interest as advancements were made over this nine year period in the development and commercialization of those components. The use of silicon carbide power switches was beginning to appear more economically feasible. That development spurred further development of materials that could be used in the inverter/converter environment at the much higher temperatures where silicon carbide devices could operate. New types of capacitors were offered to researchers that altered the design of electric drive systems. Copper prices soared. The previous intention of the auto industry to use permanent magnet motors (which are inherently more compact and efficient) was called into question as the world realized that China controlled the market of rare earth magnets and therefore the price and availability.

Much work remains to be done to incorporate newly available materials, components, and evolving vehicle architectures. Unfortunately, the world-wide economic downturn hit the auto industry hard. The decision was made to halt this project, and it terminated in September 2009.

V. SUBJECT INVENTIONS

1. J. S. Hsu, G. J. Su, D. J. Adams, J. M. Nagashima, C. Stancu, D. S. Carlson, and G. S. Smith, *Utilizing Zero-Sequence Switchings for Reversible Converters*, U.S. Patent 6,831,442, December 14, 2004. Assignees: Oak Ridge National Laboratory managed by UT-Battelle, LLC (Oak Ridge, TN) and General Motors Corporation (Torrance, CA).

2. J. S. Hsu, G. J. Su, D. J. Adams, J. M. Nagashima, C. Stancu, D. S. Carlson, and G. S. Smith, *Motor Stator Using Corner Scraps for Additional Electrical Components*, U.S. Patent 6,707,222, March 16, 2004. Assignee: Oak Ridge National Laboratory managed by UT-Battelle, LLC (Oak Ridge, TN)

3. D. S. Carlson, J. S. Hsu, J. M. Nagashima, C. C. Stancu, D. J. Adams, G. J. Su, and G. S. Smith, *Auxiliary Power Generation in a Motor Transformer*, U.S. Patent No.

7,092,267, August 15, 2006. Assignees: General Motors Corporation (Torrance, CA) and Oak Ridge National Laboratory managed by UT-Battelle, LLC (Oak Ridge, TN).

VI. COMMERCIALIZATION POSSIBILITIES

GM has licensed the intellectual property developed under this CRADA. Use of these technologies will depend on the technological approach that is ultimately chosen for hybrid electric vehicles. These new technologies were proven viable and advanced the current state of the technologies utilized in the electric drive systems of these types of vehicles. The speed with which these fuel-efficient vehicles will be available in the marketplace depends on a large number of variables such as the cost and availability of fuel, development of fuel cells so that they are cost-effective alternatives, government incentives or directives, advancement in material development, availability of materials, etc.

VII. PLANS FOR FUTURE COLLABORATION

GM was faced with severe financial problems due to the world-wide economic downtown in the last year or so, threatening the company's existence. With new and extreme financial constraints, even though GM had repeatedly stated their continued interest in the value of funding and working with ORNL, the CRADA expired at the end of 2009, ending the nine year collaboration. Any future collaboration will depend on the direction GM chooses for further development and the availability of funds to involve ORNL.

VIII. CONCLUSIONS

GM provided funds to ORNL and contributed in-kind research to advance technologies used in the electric drive systems of various types of hybrid vehicles. The research began with concepts or general ideas presented by GM and progressed to solutions. The first part of the work concentrated on modifying major components of the existing traction inverter/drive to develop low cost, robust, accessory power.

After successfully fulfilling the initial objective, the direction and duration of the CRADA was modified and GM provided additional funding to continue the collaboration. ORNL provided the basic development for implementing a cascaded inverter technology into hybrid and fuel cell vehicles. The basic development for implementing inverter and converter topologies and new technology assessments for hybrid vehicle applications then continued, including the use of high temperature components in drive systems.

This CRADA continued for nine years with GM providing $1.2M in funding to ORNL as well as their own research contributions and providing equipment and components. Intellectual property was successfully developed that resulted in three joint patents being issued and subsequently licensed by GM.

DISTRIBUTION

Internal

1. D. J. Adams
2. A. D. Brock (ORNL OTT)
3. R. L. Graves
4. J. B. Green, Jr.
5. J. S. Hsu
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9. R. L. Hamilton, DOE-Partnerships Office, hamiltonrl@oro.doe.gov.
10. D. R. Hamrin, ORNL Office of Technical Information and Classification, Bethel Valley Road, Bldg. 5300, Oak Ridge, Tennessee 37831-6254.
11. S. A. Rogers, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.
12. G. S. Smith, General Motors Advanced Technology Center, 3050 Lomita Boulevard, Torrance, California 90505.