Experimental Results and Design Guidelines Derived from the Testing of a 2 MW, 250 Hz, Auxiliary Resonant Commutated Pole Bi-Directional Converter

J.D. Herbst, R.F. Thelen, A.L. Gattozzi, and A.S. Williams
Center for Electromechanics
The University of Texas at Austin
1 University Station, R7000, Austin, TX 78712

Abstract- **An auxiliary resonant commutated pole (ARCP) converter, rated for an output of 2 MW at 250 Hz, has been built and has undergone preliminary tests at the University of Texas at Austin Center for Electromechanics (UT-CEM). Experimental results are reported on its testing as the bi-directional link between a power dc bus and a flywheel energy storage system. Design issues encountered in the course of development of the converter and the system are discussed and some considerations are made regarding the application of soft-switching ARCP-type converters versus their hard-switched counterpart.**

Index: Resonant power converters, ARCP converters, soft-switching converters.

I. INTRODUCTION

An auxiliary resonant commutated pole (ARCP) converter, rated for an output of 2 MW at 250 Hz, has been built and has undergone preliminary tests at the University of Texas at Austin Center for Electromechanics (UT-CEM). This work is part of the Advanced Locomotive Propulsion System (ALPS) project sponsored by the Federal Railroad Administration. The converter is the bi-directional link between the power dc bus of the locomotive and a 480 MJ, 15,000 rpm energy storage flywheel driven by an induction motor/generator. During charging of the flywheel, the converter takes power from the dc bus to drive the induction machine as a motor and accelerate the flywheel. During discharging of the flywheel, the converter takes variable frequency ac power from the induction machine now operating as a generator and feeds power to the dc bus. The flywheel energy storage system shares the dc bus with the prime power source, an alternator driven by a gas turbine with rectified electrical output, and with the principal load, the ac electric drives providing traction for the locomotive. A block diagram of the overall ALPS topology is shown in Fig. 1 and a photograph of the system taken during no-load test is shown in Fig. 2. Fig. 3 shows the motor/generator mounted on the flywheel during loaded tests and the ARCP converter itself is shown in Fig. 4. More complete descriptions of the ALPS system and its various components are available in the literature [1]. The focus of this paper is on the bi-directional power converter shown in the diagram and whose specifications are given in Table 1.

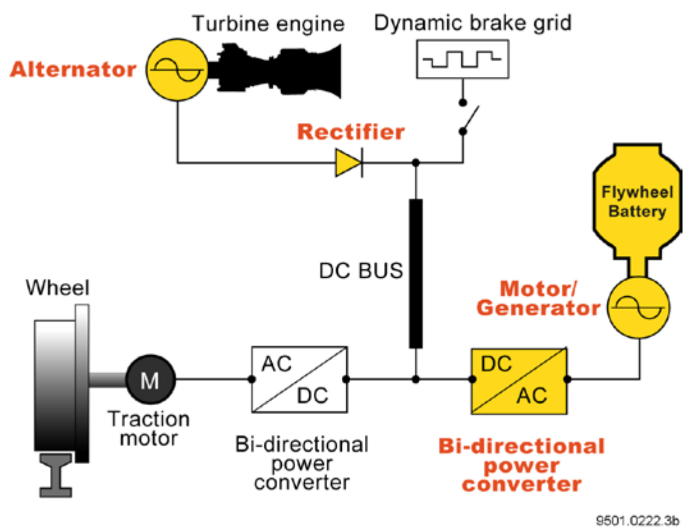

Figure 1. Schematic diagram of the ALPS system topology

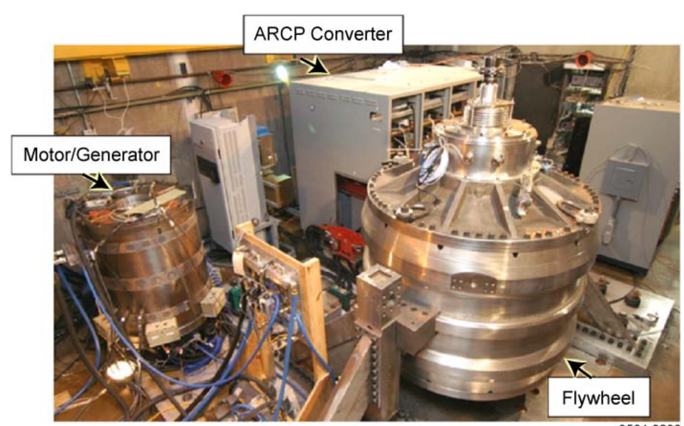

Figure 2. The ARCP converter driving the induction machine during no-load and locked-rotor testing

9501.0294

Figure 3. The motor mounted on the flywheel during loaded tests.

9501.0295

Figure 4. The ARCP converter of UT-CEM

TABLE I
ALPS ARCP INVERTER DESIGN PARAMETERS

Bus Voltage	Minimum Nominal Maximum	1,000 Vdc 1,960 Vdc 2,400 Vdc
Output	Voltage, L-L Current , L	1,100 Vac 1,200 A
Frequency	Output fundamental. Switching Commutation	0 ~ 250 Hz 4 kHz 40 kHz

II. THE ARCP SOFT SWITCHING DRIVE

The ARCP converter is rated for constant V/Hz operation from zero to 200 Hz and for constant voltage operation at 1,100 V 3-phase from 200 Hz to 250 Hz. In this application it has to transfer up to 2 MW of power at a maximum current of 1,000 A between a 1,960 V dc bus and an induction machine that can act as a motor or generator. A two-pole induction motor/generator design was selected to limit the drive power frequency to 250 Hz at the flywheel's top speed of 15,000 rpm. By operating at high, direct-drive speeds the motor is physically smaller, however, this also limits its thermal capacity, making the drive harmonic loading of greater concern. Because of these considerations, a variable speed motor drive was sought with under-modulated PWM output over the full frequency and power range. To minimize the harmonic content of the waveform and consequent motor heating the converter switching frequency was set at 4,000 Hz, which is sixteen times the maximum frequency output. Furthermore, space restrictions and efficiency considerations made loss minimization within the converter itself a high priority leading to the decision of adopting a soft-switching design and the eventual selection of the ARCP topology.

ARCP inverters have been the subject of much research because of their potential for reduced losses and smaller packaging [2 through 8]. The converter built and under test at UT-CEM is identical in its architecture to the original one presented in [2] to which the reader is referred for a thorough description of its principles. Its schematic diagram is shown in Fig. 5.

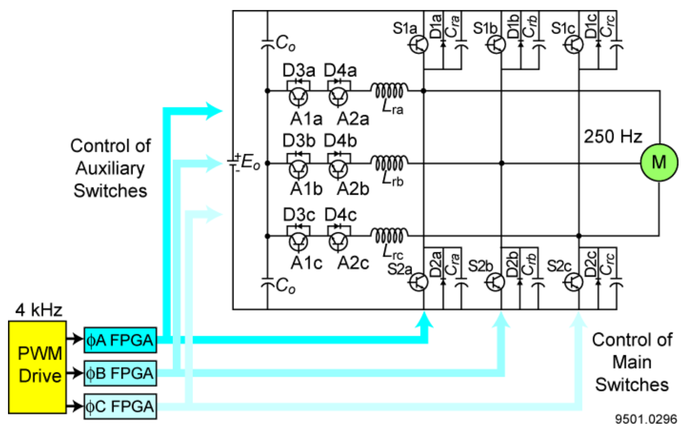

Figure 5. Schematic diagram of the ARCP converter built at UT-CEM.

For simplicity all switching elements in Fig. 5 are shown as single devices but in reality each main switch (labeled S1 and S2 in each phase) consists of three parallel sets of two IGBTs in series with individual snubber capacitors, and each auxiliary switch and inductor set (labeled A1 and A2 plus series inductor in each phase) consists of three parallel sets of two IGBTs in opposition and an inductor in series. A detailed schematic of one pole is given in Fig. 6 and the component parameters are presented in Table 2. All power switches used are functionally identical devices rated at 1,700 V and 1,200 A and are either Dynex DIM1200DDM17-E000 or Powerex CM1200DC-34N. The devices are liquid cooled with a mixture of water and glycol.

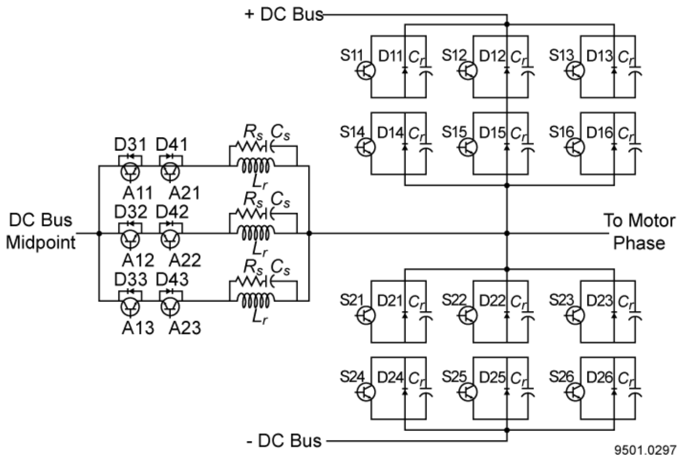

Figure 6. Actual circuit of one phase of the ARCP. Nominal bus voltage is ±980 V. Bus mid-point is a virtual ground.

TABLE 2
ARCP CONVERTER PHASE COMPONENT VALUES

Resonating Capacitor	Cr	0.45	μF
Resonating Inductor	Lr	10	μH
Snubber Capacitor	Cs	1.2	μF
Snubber Resistor	Rs	1.0	Ω

It is well known [2] that the function of the inductors in the auxiliary branches is to resonate with the snubber capacitors of the main switches in order to bring the voltage across the whole main switch set to zero prior to turning that main switch set ON. Subsequently, after the zero-voltage turn-on of the main switches, the current through the inductors will fall and when it crosses zero the auxiliary switches will be turned OFF (zero-current turn-off). This should result in the theoretical avoidance of switching losses in both main and auxiliary switches.

A fact that has not received much attention in the literature is that the switching action in the auxiliary circuits occurs against the fairly large inductance of the resonating inductors. As will be discussed in more detail in a subsequent section, this can lead to the generation of inductive voltages that are quite large and that, when summed to the existing dc open circuit voltage, can result in damage to the auxiliary switches and other circuit components. Therefore, it is necessary to limit the voltage transients by means of snubbers placed either across the auxiliary switches themselves or across the inductors. In the ALPS converter, it was decided to place the snubbers across the inductors to preserve the integrity of the switches and avoid the complicating presence of a current in the auxiliary branches at all times. This led to the RC snubbers shown in Fig. 6.

It was decided to leverage the software developed and contained in a commercial off the shelf PWM drive control board to provide the basic six-gate switching sequence. These signals are captured in field programmable gate arrays (FPGA), one per phase, which have been programmed to transform the sequence to the twelve-switch requirements in the ARCP configuration. The outputs of the FPGAs are conveyed via optical fibers to gate drive boards, which individually gate each IGBT in a switch-group after a verified voltage zero is detected across the switch or zero current is detected through the switch.

It is fundamental to the operation of an ARCP inverter to turn the main switches S1 and S2 ON when the voltage across them is zero and to turn the auxiliary switches A1 and A2 OFF when the current through them is zero. The symmetric transitions, turning S1 and S2 OFF or turning A1 and A2 ON, are already expected to take place at zero voltage or zero current because of their timing in the cycle and because they are further aided by the reactive elements in the circuit, respectively the snubber capacitors and the in-line inductors. This results in theoretically lossless switching in both cases. A rather complex sensing system must be designed with attendant control circuitry to accomplish commutation only when these conditions of zero crossing are satisfied.

Fig. 7 presents a schematic diagram of the overall control system for the ARCP converter, including a PWM filter and of a discharge board across the lower main switch sections of the inverter. These devices and their need were discussed in [9]. Here it suffices to recall that the PWM filter is necessary to eliminate from the commercial PWM generator pulses that are too short and, therefore, incompatible with the resonance cycle of the converter. As for the discharge boards (one per phase), they are dictated by the need to assure an orderly and predictable start of the drive cycle with the initial condition of zero voltage across the S2 switches forcibly imposed at time t = 0.

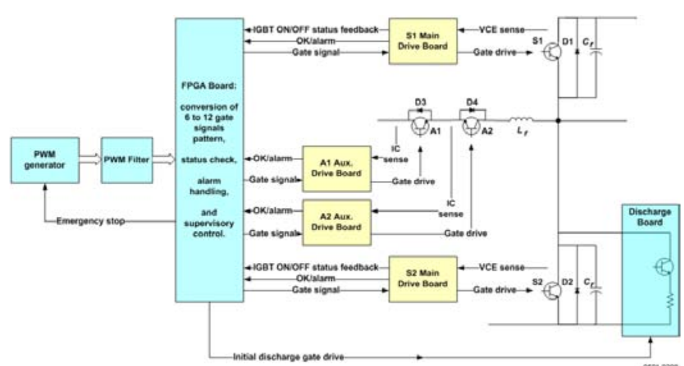

Figure 7. ARCP control system diagram. Only one phase and single devices are shown.

III. TEST RESULTS

The ARCP preliminary test set up is shown in Fig. 8. For simplicity, initial tests were conducted with a resistive load bank and a dc bus supplied from the utility supply through a step-up transformer and passive rectifier. For safety during flywheel testing, a auxiliary 250 kW variable speed drive with braking capability was also set up in parallel to the ARCP converter.

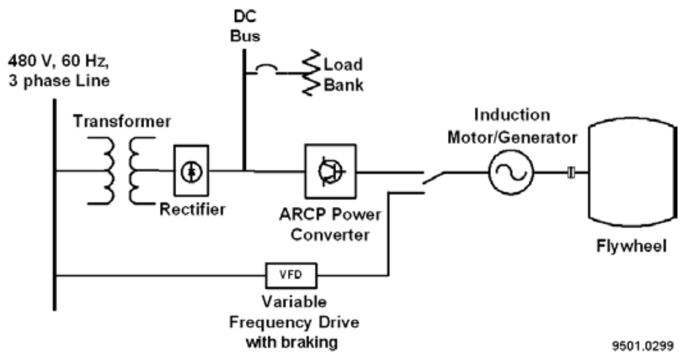

Figure 8. ARCP preliminary test set up.

The preliminary test set up shown in Fig. 8 allows the testing of the ARCP first as an inverter, accepting power from the dc bus and driving up to speed the flywheel via the induction machine working as a motor, and then as a regenerative drive accepting power from the flywheel driving the induction machine as a generator and dissipating it into the dc load bank.

The first tests run were with the ARCP operating as an inverter. Initially, the induction motor was disconnected from the flywheel (Fig. 2) and was run at no-load. Representative waveforms during no-load tests are reported in Figs. 9 and 10. Fig. 9 shows voltage waveforms collected during the highest speed run conducted at no-load, namely at 11,400 RPM, 190 Hz. It was necessary to insert a 1.25 mH line inductance in each phase in order to conduct these tests. Operation above 190 Hz has been prevented to date by noise issues that trip the control system of the inverter. Fig. 10 shows the auxiliary currents registered under the same circumstances.

Tests with the induction machine driving the flywheel (Fig. 3) under load were also run. To date these tests have been limited to 33.34 Hz, 2,000 RPM, because of technical issues arising in connection with the magnetic bearing controller of the flywheel. The magnetic bearing controller was being affected by externally generated noise resulting in delevitation and contact with the touchdown bearings. These noise issues are being investigated as of this writing.

Figs. 11 and 12 show the results obtained under load at 33.34 Hz, 2,000 RPM for the same set of voltages and currents as in the previous no-load case. The motor phase voltages and line currents at the inverter output for this loaded case are shown in Figs. 13 and 14. In general, it can be said that the voltage and current waveforms are quite well behaved, follow the expected pattern, and are well balanced. The ringing on the voltage traces especially at turn-on and turn-off, while undesirable, is not excessive. It is hoped that a resolution of the noise problems will allow resumption of the tests as soon as possible.

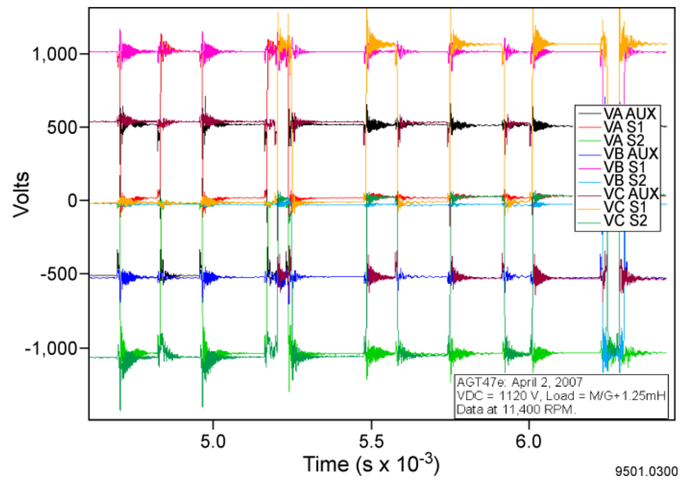

Figure 9. Voltage traces during high speed run (11,400 RPM, 190 Hz) with the ARCP inverter driving the induction motor at no-load with a 1.25 mH additional load inductance per phase. Suffixes A, B, C refer to the three phases of the ARCP and suffixes AUX, S1, S2 refer to voltages across the auxiliary branches, the top set of main switches, and the bottom set of main switches respectively.

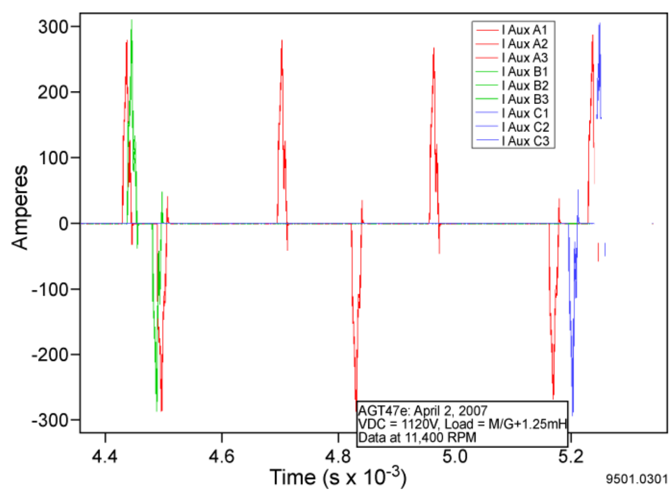

Figure 10. Auxiliary current traces during high speed run (11,400 RPM, 190 Hz) with the ARCP inverter driving the induction motor at no-load with a 1.25 mH additional load inductance per phase. Suffixes A, B, C refer to the three phases of the ARCP and suffixes 1-3 refer to the three auxiliary branches per phase. The pulses are positive for current flowing from left to right in the auxiliary branches shown in Figure 6, negative for current flowing in the opposite direction.

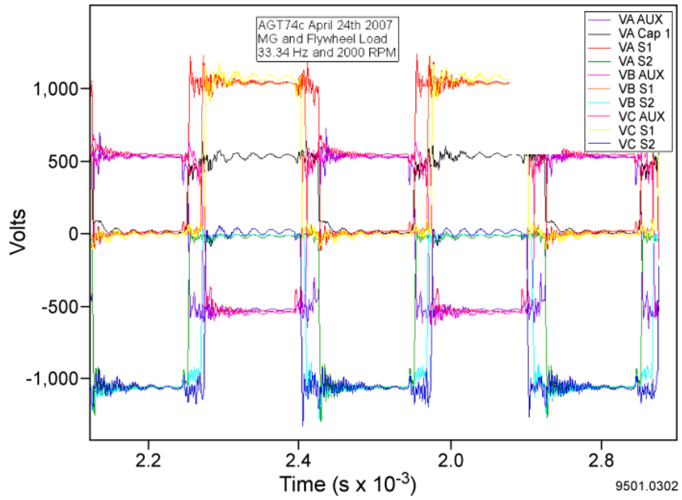

Figure 11. ARCP converter switch voltages at 33.34 Hz (2,000 RPM) driving motor with flywheel load. Suffixes A, B, C refer to the three phases of the ARCP and suffixes AUX, S1, S2 refer to voltages across the auxiliary branches, top set of main switches, and bottom set of main switches respectively. Suffix Cap1 refers to one of the dc bus capacitors (six were used, in a two series, three parallel configuration).

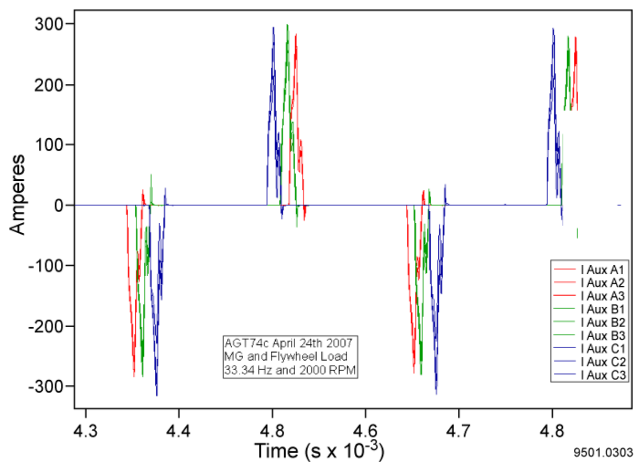

Figure 12. ARCP converter auxiliary currents during 2,000 RPM, 33.34 Hz, flywheel run. Suffixes A, B, C refer to three phases of the ARCP and suffixes 1-3 refer to three auxiliary branches per phase. Pulses are positive for current flowing from left to right in auxiliary branches shown in Fig. 6, negative for current flowing in opposite direction.

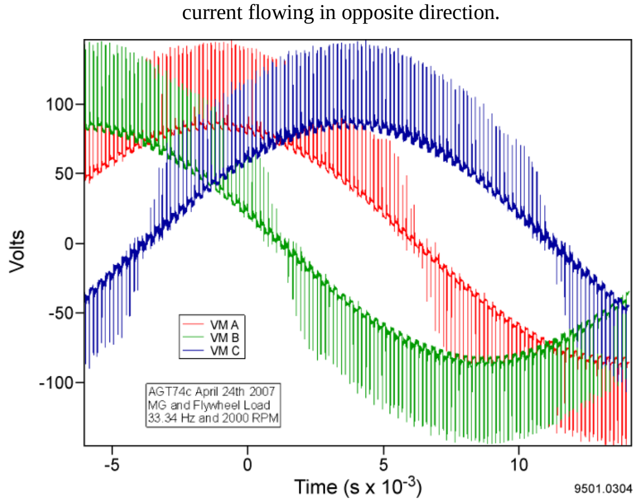

Figure 13. Terminal motor voltages at 33.34 Hz with the flywheel load at 2,000 RPM

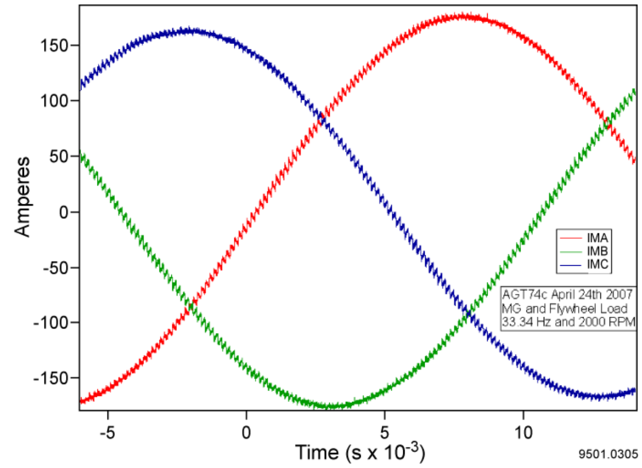

Figure 14. Motor line currents at 33.34 Hz and 2,000 RPM with flywheel load.

IV. DESIGN CONSIDERATIONS

Some of the technical challenges encountered in the development of the UT-CEM ARCP converter have been discussed elsewhere [9, 10, 11]. Two in particular will be highlighted here and both concern the operation of the auxiliary circuits. It has already been mentioned above that it is necessary to provide snubbers for either the auxiliary switches or the resonating inductors to avoid large and potentially destructive voltage transients. The most dangerous transients are connected with the reverse recovery current of the diodes in the auxiliary branches. Thus, referring to Fig. 5, the reverse recovery current of diode D4, flowing in opposition to the auxiliary current direction produces a large inductive voltage kick at the resonating inductor terminals that adds to the voltage that must be withstood by the A1 switch as it is turned OFF. Despite the relatively small reverse recovery current levels, this inductive voltage spike can be considerable, forcing the use of switches rated for at least two times the value of the dc bus voltage in the auxiliary, whereas, in theory, a switch rated for even less than the dc bus voltage may suffice in that location. The necessity of limiting the inductive voltages generated in the auxiliary circuits by means of RC snubbers has negative consequences from the standpoint of energy consumption. The tight control of all timing events in an ARCP converter imposes very stringent requirement to insure successful commutation. This has already been mentioned in connection with the need to filter out all PWM pulses of width shorter than the resonating cycle time. Likewise, a snubber capable of dissipating the inductive energy in a switching event in a time sufficiently short not to compromise the commutation cycle is needed. In the UT-CEM ARCP this resulted in an additional 25 kW of power loss (1.25% of rated power) in the snubbers alone at no-load. While the snubbers can perhaps be optimized with additional design work, it is unlikely that their loss will be reduced considerably leading to the conclusion that an ARCP converter will be saddled with a penalty in efficiency from the auxiliary snubbers on the order of 1%.

The second design issue concerns the ability of the converter to commutate the load current. The commutation in the ARCP converter is driven by the resonating auxiliary currents. The resonance cycle will be more effective the less energy is lost in the process and, in fact, it has been experimentally verified that it is very sensitive to the overall series resistance in the path of the resonating current. The presence of just a few mΩs of resistance in the auxiliary current path can adversely affect its commutation ability. This imposes the use of very high quality resonating inductors, capacitors, intervening connecting cables (Litz wire was used in the ALPS system), and a well planned conductor routing scheme. Within the practical constraints imposed by the construction of a large power converter with real devices, one may find that commutation becomes more difficult as the load current increases and may even fail because of insufficient auxiliary current driving the process. Some suggestions to alleviate this problem have been proposed keeping the ARCP essentially intact [12, 13]. An alternative is to modify the topology by deriving the auxiliary current excitation directly from the DC bus rails without the use of the virtual ground point between them. This alternative shown in Fig. 15 is reproduced from [11] where it is discussed in more detail. Although this approach has not yet been tried on the UT-CEM ARCP, it is one of the items on the agenda for future work. Incidentally, this topology may sidestep the need for auxiliary snubbers, as the diode reverse recovery current will not flow through the inductor; thus, a major efficiency penalty would be avoided.

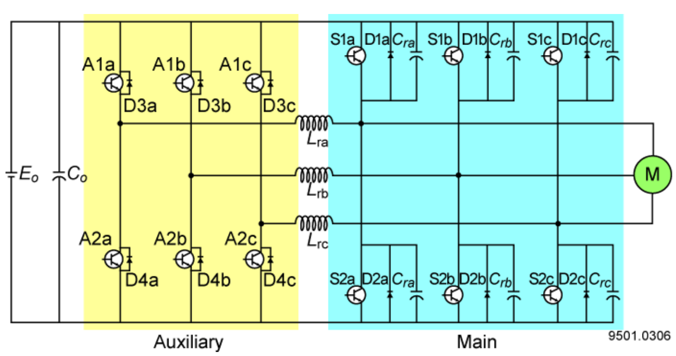

Figure 15: New topology for the ARCP converter

It is obvious that the soft-switched ARCP converter is a more complex machine than its hard-switched counterpart, both from the standpoint of the amount of hardware used and the sophistication of the control system. The whole exercise is predicated on the desire to increase efficiency, reduce losses, and extend its rating by minimizing the switching losses in the main converter bridge. It is natural, therefore, after two decades of development, to ask the question whether it is still advantageous to pursue a resonant converter design in a high power application. This question has in fact been asked not only for ARCP type converters but for resonant converters in general and the answer given puts in perspective the niche where this technology will find its best application. It is estimated that, with the use of present day devices, achievable switching loss reductions are on the order of 5% [14]. This is a much smaller figure than claimed early on, but it recognizes the fact that there has been a steady improvement in the performance of switching devices in the last two decades. Thus, many of the original incentives behind the adoption of a resonant architecture may have disappeared. It is a fact, however, that in applications where pushing the temperature limits, or the operating frequency, or the physical size puts a significant strain on conventional technology or results in significant savings elsewhere in the system, the projected advantages afforded by a resonant converter may justify its use and may indeed be the only way to solve the problem. Therefore, it is expected that the ARCP converter, as one of the resonant converters proposed to date, will continue to find its best application and justification at the edges of the technology spectrum.

V. CONCLUSIONS

The design of the UT-CEM ARCP converter has been reviewed and its preliminary test results have been presented. Some of the main design issues have been discussed and possible solutions offered. The experience so far seems to confirm that hard-switched converters will dominate general purpose applications and that resonant converters will likely continue to be best suited in the most demanding applications.

ACKNOWLEDGMENT

This material is based upon work supported by Federal Railroad Administration cooperative agreement, DTFR53-99-H-00006 Modification 7, dated May 2006. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the Federal Railroad Administration and/or U.S. DOT.

REFERENCES

[1] J.D. Herbst, M.T. Caprio, and R.F. Thelen, “Advanced Locomotive Propulsion System (ALPS) Project Status 2003,” 2003 ASME Inernational Mechanical Engineering Congress and Exposition, Washington, D.C, November 15-21, 2003.

[2] R. W. De Doncker, J. P. Lyons, "The Auxiliary Resonant Commutated Pole Converter," IEEE IAS Annual Meeting, 7-12 Oct. 1990, Vol. 2, p. 1228-1235

[3] J. von Bloh, R. W. De Doncker, "Characterizing Medium-Voltage High-Power Devices under Conventional and Soft-Switching Conditions," IEEE IAS Annual Meeting, 3-7 Oct. 1999, Vol. 1, p. 373-378

[4] W. McMurray, "Resonant Snubbers with Auxiliary Switches," *IEEE Trans. Ind. Appl.*, Vol. 29, No. 2, March/April 1993, p. 355-362

[5] H. J. Beukes, J. H. R. Enslin, R. Spee, "High Power Auxiliary Resonant Commutated Pole Converters for Utility Applications," 23rd Intl. Conf. on Ind. Electron., Control & Instrum., 9-14 Nov. 1997, Vol. 2, p. 664-669

[6] S. Bernet, R. Teichmann, J. Weber, P. K. Steiner, "Evaluation of a High Power ARCP Voltage Source Inverter with IGCTs," *IEEE IAS Annual Meeting*, 3-7 Oct. 1999, Vol. 2, p. 1063-1072

[7] B. T. Kuhn, S. D. Sudhoff, C. A. Whitcomb, "Performance Characteristics and Average-Value Modeling of Auxiliary Resonant Commutated Pole Converter Based Induction Motor Drives," *IEEE Trans. Energy Conv*., Vol. 14, No. 3, Sept. 1999, p. 493-499

[8] J.-S. Lai, J. Zhang, "Efficiency Design Considerations for a Wide-Range Operated High-Power Soft-Switching Inverter," 32nd Ann. Conf. IEEE Ind. Electron. Soc., 6-10 Nov. 2005, p. 604-609

[9] A. Williams, A. Gattozzi, R. F. Thelen, "Applications of an Auxiliary Resonant Commutated Pole Converter," Applied Power Electronic Conference, Anaheim, California, U.S.A., February 25-March 2007

[10] R.F. Thelen, A.L. Gattozzi, D. Wardell, and A.S. Williams, "A 2 MW Motor and ARCP Drive for High Speed Flywheel," Applied Power Electronics Conference, Anaheim, California, U.S.A., February 25-March 1, 2007

[11] A.L. Gattozzi, R.F. Thelen, A.S. Williams, "Soft switching drive for a megawatt class, variable speed, motor/generator," Workshop on Transportable Megawatt Power Systems, The University of Texas, Austin, March 6-7, 2007

[12] J. Jiang, X. Zhou, W. Zhang, "An Improved Auxiliary Resonant Commutated Pole Inverter Using Assistant Power Source," *Proc. 3rd Int'l Power Eletcron. & Motion Control Conf.*, Vol. 1, p. 158-162, 15-18 August 2000

[13] A. Toba, T. Shimizu, G. Kimura, M. Shioya, S. Sano, "Auxiliary Resonant Commutated Pole Inverter Using Two Internal Voltage-Points of DC Source," *IEEE Trans. Ind. Electron.*, vol. 45, no. 2, p. 200-206, April 1998

[14] D.O. Neacsu, *Power Switching Converters, Medium and High Power*, Chapter 9, CRC Press 2006