An Auxiliary Quasi-Resonant Tank Soft-Switching Inverter

Fang Z. Peng, senior member, *IEEE* and Donald J. Adams

Oak Ridge National Laboratory*
P.O. Box 2009, Bldg. 9102-1, MS 8038
Oak Ridge, Tennessee 37831-8038
Phone: 865-576-7261, Fax: 865-241-6124
Email: pengfz@ornl.gov

Abstract-An auxiliary quasi-resonant dc tank (AQRDCT) inverter is presented for achieving soft-switching. An AQRDCT circuit is coupled directly across a dc bus to the inverter to generate a quasi-resonant dc bus voltage. It consists of two auxiliary switches connected in the common phase leg fashion as an auxiliary switch leg, two resonant capacitors connected in series as a resonant leg, a pair of dc capacitors connected in series as a dc tank, and a resonant inductor in series with the lower device of the auxiliary switch leg. The AQRDCT circuit resonantly brings the dc bus voltage to zero in order to provide a zero-voltage switching interval for the main inverter to switch, then quickly rebounds back to the dc tank voltage after the main inverter changes state. The auxiliary switches are turned on and off softly as well. The AQRDCT circuit absorbs only ripples of the inverter dc bus current, thus having less current stress. In addition, since the AQRDCT circuit is coupled in parallel with the dc power supply and the inverter for merely assisting soft-switching of the inverter without participating in real dc power transmission and power conversion, malfunction and failure of the tank circuit will not affect the functional operation of the inverter; thus a highly reliable inverter system is expected. A 100 kW (150 kVA) continuous power AQRDCT inverter has been built, fully tested, and put into a 22-foot electric bus for traction drive. Tested results showed good efficiency, reduced EMI, and reliable operation. This paper describes the operating principle and control and reports the test results.

I. INTRODUCTION

To reduce switching losses and alleviate electromagnetic interference (EMI), a soft switching technique has been developed for power inverters. For example, one pioneer soft-switching inverter is an active clamped resonant dc link (ACRDCL) inverter [1] developed by D. Divan et al in U.S. Pat. No. 4,864,483, issued Sept. 5, 1989. In the ACRDCL inverter, a resonant circuit, incorporated with an active clamping switch and clamping capacitor, is used as an interface between a dc power supply and a dc bus supplying the inverter. The ACRDCL resonates periodically, bringing the dc link voltage to zero once each cycle. The inverter switching devices are switched on and off at zero-voltage instants of the resonant dc link, thus achieving lossless switching. However, the ACRDCL inverter has

some disadvantages, such as, high voltage stress across the inverter switches and continuous resonant operation of the dc link. To overcome the disadvantages of the ACRDCL inverter, an auxiliary quasi-resonant dc link (AQRDCL) inverter [2] was developed by R. De Donker et al in U.S. Pat. No. 5,172,309, issued Dec. 15, 1992. The AQRDCL inverter is employed to achieve soft-switching in an inverter coupled to a dc power supply via a resonant dc link circuit. The resonant dc link circuit includes a clamping switch limiting the dc bus voltage across the inverter to the positive rail voltage of the dc supply and auxiliary switching device(s) assisting resonant operation of the resonant bus to zero voltage in order to provide a zero-voltage switching opportunity for the inverter switching devices as the inverter changes state. There are many other resonant and quasi-resonant dc link inverters [3-8].

Despite their advantages, soft-switching resonant and quasi-resonant dc link inverters have the following common disadvantages: (1) The resonant dc link circuit acts as an interface (i.e., a dc-to-dc inverter) between the dc power supply and the inverter and needs to transmit real power and to carry dc current from the dc power supply to the inverter or from the inverter back to the dc power supply via switch(es) and/or resonant component(s), which can lead to significant power losses; (2) The voltage clamping, voltage control, and charge balancing become difficult due to the real power transmission; (3) The current stress on the auxiliary switch(es) and clamping switch(es) is at least as high as that on the inverter main switches; and (4) Two resonant dc link circuits are needed in some resonant DC link circuits for an ac-to-dc-to-ac inverter to implement soft-switching at both the ac-to-dc power conversion stage and the dc-to-ac power conversion stage.

Additional aspects about controversial soft switching are cost and control difficulties, since soft-switching inverters rely on additional devices that increase cost and control complexity. Therefore, many contributors continue searching for new soft-switching power inverters that can overcome or alleviate the disadvantages of today's soft-switching inverters.

An auxiliary quasi-resonant dc tank (AQRDCT) inverter is presented for achieving soft-switching. An AQRDCT circuit is coupled directly across a dc bus to the inverter to generate a quasi-resonant dc bus voltage. The AQRDCT circuit resonantly brings the dc bus voltage to zero in order to provide a zero-voltage switching interval for the main inverter to switch, then quickly rebounds back to the dc tank voltage after the main inverter changes state. The auxiliary switches are turned on and off softly as well. The AQRDCT circuit has several advantages over traditional resonant links, such as less current stress and more reliability. A 100 kW (150 kVA) continuous power AQRDCT inverter has been built, fully tested, and put into a 22-foot electric bus for traction drive. This paper describes the operating principle and control and reports the test results.

II. AQRDCT INVERTER AND OPERATING PRINCIPLE

A. AQRDCT Inverter

Fig. 1 illustrates the proposed AQRDCT inverter. The AQRDCT inverter includes a dc power supply shown as *Vdc* with an internal dc inductor, *Ld*, connected to a dc bus and a quasi-resonant dc tank circuit coupled across the dc bus, which directly feeds the main inverter. It should be noted that the AQRDCT is employed to generate a quasi-resonant dc bus voltage while dc power is transmitted from the dc supply to the inverter or from the inverter back to the dc supply directly. This is advantageously different from the resonant and quasi-resonant DC link inverters. The AQRDCT circuit consists of a pair of resonant capacitors *Cr1* and *Cr2* connected in series as a resonant leg, a pair of dc tank capacitors *Ct1* and *Ct2* connected in series as a tank leg, a pair of auxiliary switches (diodes) *Sap (Dap)* and *San (Dan)* connected in series as an auxiliary leg, and a resonant inductor *Lr*. The tank capacitors *Ct1* and *Ct2* are equivalent to the traditional dc capacitor. They are 4,000 µF electrolytic caps in the 100 kW prototype. The resonant capacitors *Cr1* and *Cr2* are 0.44 µF. The resonant inductor is 0.8 µH. The dc power supply can be implemented as shown in Fig. 2, where a dc choke or ac inductor is used. Such dc or ac inductors are commonly used in ac drives.

B. AQRDCT Operating Principle

Fig. 3 shows the equivalent circuit of the AQRDCT inverter of Fig. 1 as seen from the AQRDCT circuit and illustrative waveforms for understanding the operation. In Fig. 3, switching device *Seq* and diode *Deq* represent the equivalent switch and diode of the main switching devices, *S1-S6*, and the antiparallel diodes, *D1-D6*, of the main inverter, respectively. The current that flows into the AQRDCT circuit is the tank current, *Io*, represented by

$$Io = Id - Ii, \tag{1}$$

where *Id* is the dc supply current and *Ii* is the inverter dc bus current as shown in Fig. 1. Therefore, the AQRDCT circuit absorbs only the difference of the inverter bus current and the

dc supply output current. It should be also noted that an average value of tank current *Io* equals zero neglecting losses of the AQRDCT circuit. Advantageously, current stress of the auxiliary switching devices *Sap (Dap)* and *San (Dan)* is much smaller than that of the devices used in the existing resonant and quasi-resonant inverters. The following section describes the detailed operating principle and control sequence. It explains how the AQRDCT circuit first brings the dc bus voltage, *Vbus*, to zero and generates a brief zero-voltage interval for the main switching devices to switch, after which it rapidly brings the bus voltage back to normal.

C. AQRDCT Operating Modes and Control Sequence

Fig. 4 shows the operating modes and control sequence (gating timings) during one switching instance. Figs. 5a through 5l show each operating mode and its current flow in the AQRDCT inverter, where the bold-lined device(s) and component(s) conduct current. Fig. 5a shows the initial condition, assuming tank current *Io* initially flows in clamping diode *Dap*. Clamping switch *Sap* is gated on although it carries no current. When the main inverter needs to change states, the auxiliary resonant circuit is triggered into conduction by gating on auxiliary switch *San* at t1 as shown in Figs. 4 and 5b. A current is established in resonant inductor *Lr* while holding clamping switch, *Sap*, closed. When the current in resonant inductor, *Lr*, becomes larger than *Io*, clamping switch, *Sap*, conducts at t1′ and the current path is shown in Fig. 5c. Further when this resonant inductor current reaches a specified level (*Io+Ip*)[1], clamping switch *Sap* is gated off at t2. Consequently, this resonant inductor current charges and discharges resonant capacitors *Cr1* and *Cr2*, respectively, thus assisting resonance of the dc bus down to zero voltage as shown in Fig. 5d. After the dc bus voltage, *Vbus*, reaches zero and the resonant inductor current attempts to negatively charge resonant capacitor, *Cr2*, the equivalent diode, *Deq*, takes over the surplus current clamping the dc bus voltage to zero as illustrated in Fig. 5e. At this point, all the main switches of the inverter are gated on, thus forming a shorted circuit (equivalently producing zero-vector output). In other words, the inverter dc bus current, *Ii*, circulates through the inverter itself. The resonant inductor current decreases since voltage *V2* is against the current. When the resonant inductor current becomes less than dc supply current, *Id*, equivalent switch *Seq* conducts at t3′ and its current path is shown in Fig. 5f. The resonant inductor current will decay to zero and reverse its direction. Diode *Dan* picks up the current as shown in Fig. 5g. After the reverse resonant inductor current reaches a specified level the inverter changes state at t5 and equivalent switch *Seq* turns off. The resonant inductor current charges and discharges resonant capacitors Cr2 and Cr1, respectively, thus bringing the dc bus voltage back to the dc tank voltage (Fig. 5h). When the dc bus voltage attempts to overshoot the

---

[1] *Ip* is a bias current to compensate losses and ensure voltage to resonate to zero.

Fig. 1. Proposed AQRDCT inverter topology.

Fig. 2. Possible DC power supplies for the AQRDCT inverter.

Fig. 3. Equivalent circuit of AQRDCT and operating principle.

Fig. 4. Operating modes and control sequence.

dc tank voltage, clamping Diode, *Dap*, conducts as shown in Fig. 5i. At this point, clamping switch *Sap* is gated on and will conduct when the resonant inductor current becomes less than (*Id−Ii*) as shown in Fig. 4j. The resonant inductor current decreases to zero, the dc bus voltage is clamped to the dc tank voltage through clamping switch *Sap* as shown in Fig. 5k (back to Mode 0). Here it is assumed that the tank current *Io* reverses after the main inverter changes state at t5 as shown in the solid line in Fig. 4. However, if *Io* changes to a positive level as shown in dashed line in Fig. 4, clamping diode *Dap* conducts and clamps the bus voltage to the tank voltage as shown in Fig. 5l. The dc tank voltage is automatically balanced at a voltage level, *Vt*, slightly higher

than the dc supply voltage, *Vdc*, so that the average value of the resonant dc bus voltage, *Vbus*, is equal to the dc supply voltage, *Vdc*, neglecting losses in dc inductor, *Ld*, and clamping devices, *Sap* and *Dap*.

When a relatively high tank current, *Io*, initially flows in clamping switch, *Sap*, there is no need to gate on auxiliary switching device *San*. A sufficiently high tank current, *Io*, can discharge resonant capacitor, *Cr2*, and bring the dc bus voltage to zero by directly turning off clamping switch, *Sap*. After the dc bus voltage reaches zero, equivalent diode, *Deq*, takes over tank current *Io* and clamps the dc bus voltage to zero. Then the same control just described is employed to resonate the dc bus voltage back to the tank voltage.
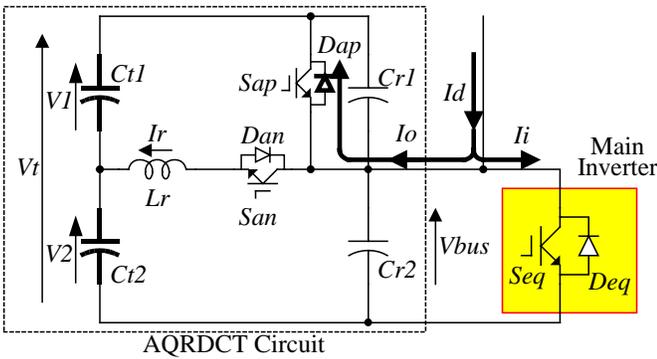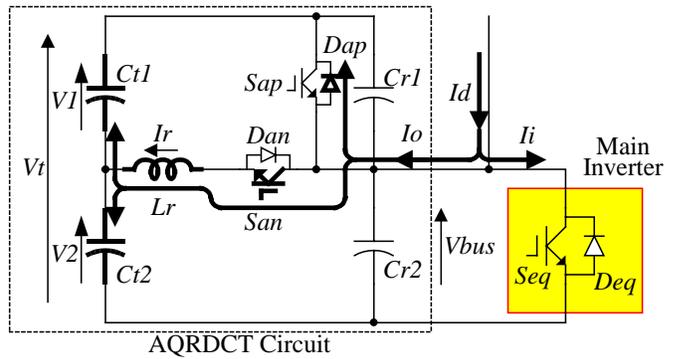

Fig. 5a. Current path at Mode 0 (before t1).
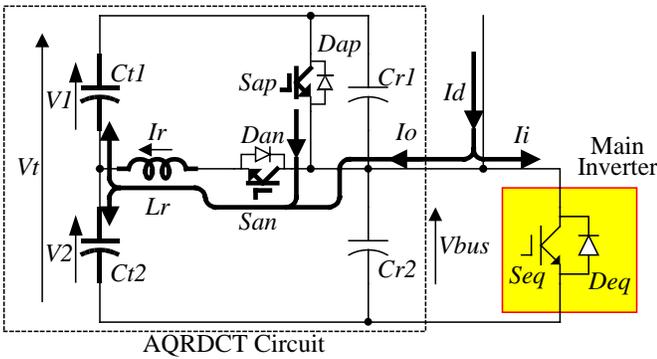

Fig. 5b. Current path at Mode 1 (t1~ t1′).
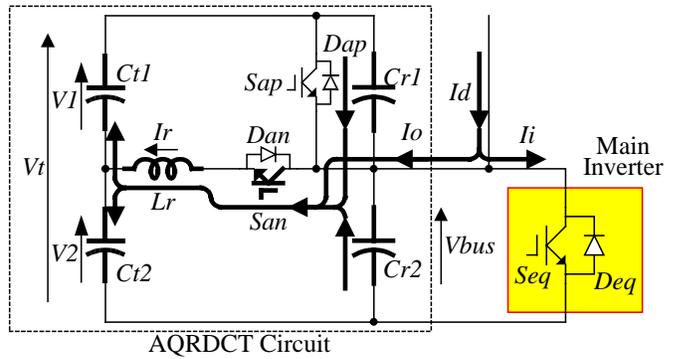

Fig. 5c. Current path at Mode 1 (t1′~t2).
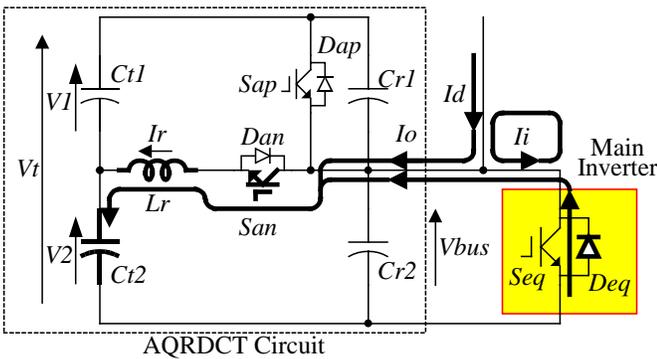

Fig. 5d. Current path at Mode 2 (t2~t3).
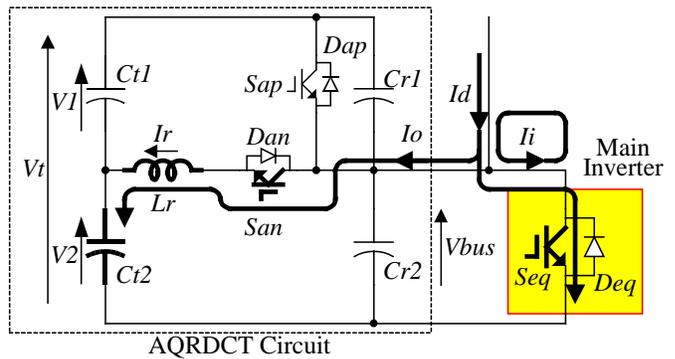

Fig. 5e. Current path at Mode 3 (t3~t3′).

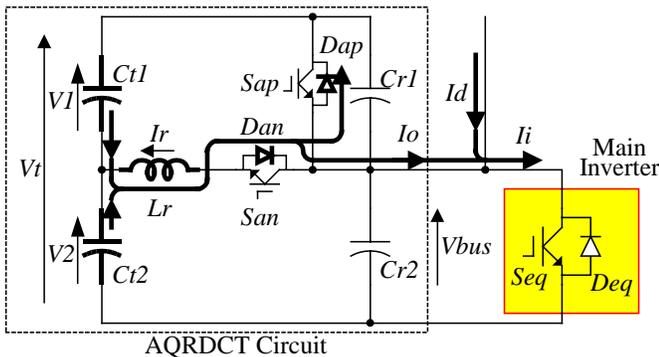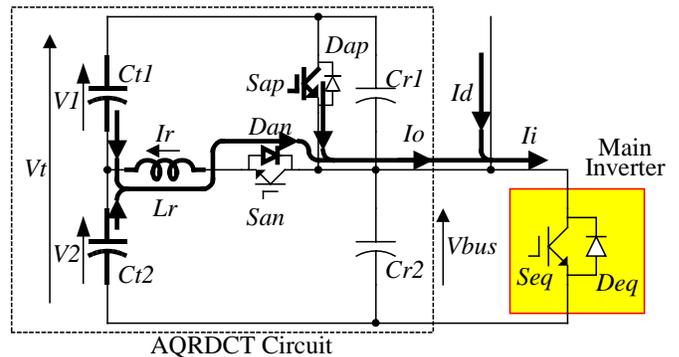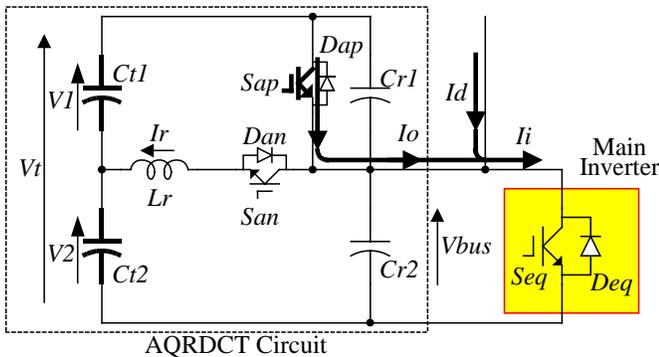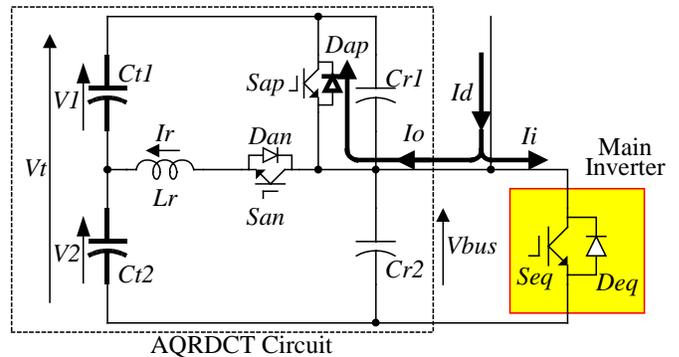Fig. 5f. Current path at Mode 3 (t3′~t4).
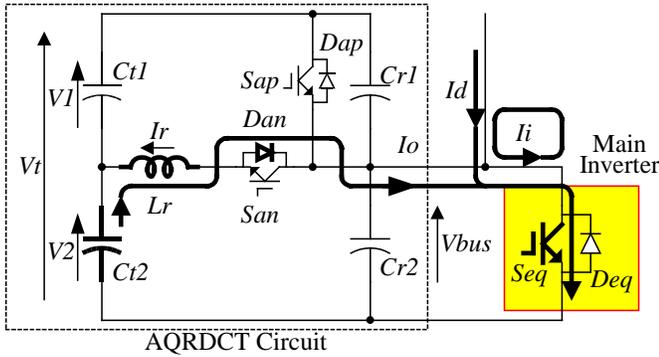
Fig. 5g. Current path at Mode 4 (t4~t5).
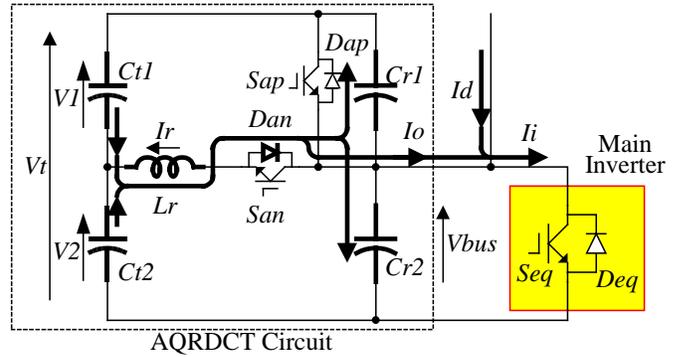
Fig. 5h. Current path at Mode 5 (t5~t6).

Fig. 5i. Current path at Mode 6 (t6~t6′).

Fig. 5j. Current path at Mode 6 (t6′~t7).

Fig. 5k. Current path at Mode 0 (after t7).

Fig. 5l. Current path at Mode 0 (after t7).

III. 100 kW-150 kVA AQRDCT INVERTER IMPLEMENTATION, CONTROL, AND RESULTS

A 100 kW (150 kVA) AQRDCT inverter has been built. The soft-switching control was implemented on an Altera chip (EPM5130). After extensive testing at lab, the inverter was used in the traction drive of a 22-ft electric bus. Fig. 6 shows the 100 kW AQRDCT inverter and the electric bus photos. The AQRDCT inverter has been put into the bus to drive an induction motor. The dc power supply is the traction battery rated at 338V when fully charged. The dc terminal voltage can rise to nearly 400V during regenerative braking. The rated motor current is 300A rms.

Fig. 7 shows some waveforms during acceleration of the vehicle. Figs. 8 and 9 show zoom-ups of Fig. 7. When the main inverter wants to switch, a resonant inductor current pulse, Ir, is generated by gating on the auxiliary switch San. The resonant inductor current, Ir, discharges and charges the resonant capacitors, $Cr2$ and $Cr1$, thus bringing the dc bus voltage, $Vbus$, down to zero. When the dc bus voltage reaches zero, all the main switches are gated on to maintain zero voltage level and produce a negative resonant current pulse. After the main inverter switches change to a desired state, the established negative resonant inductor current pulse brings the dc bus voltage back to normal. Fig. 8 clearly shows this operation. In Fig. 9, it is shown that the resonant inductor current varies with the tank current Io. When a

Fig. 6. Photos of the 100 kW soft-switching inverter and electric bus.
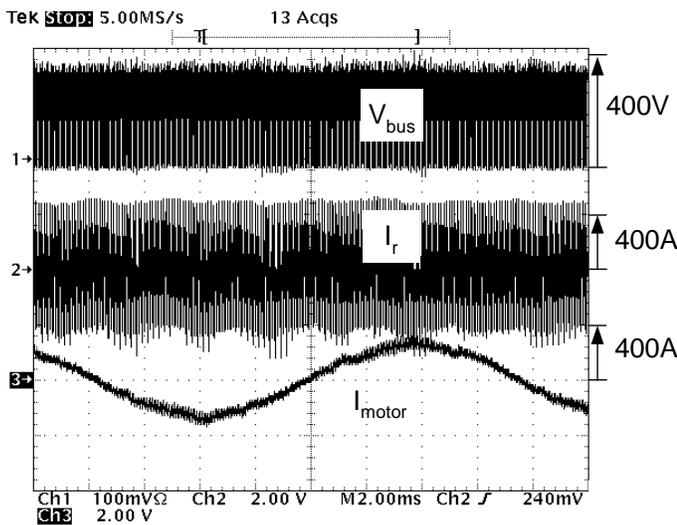

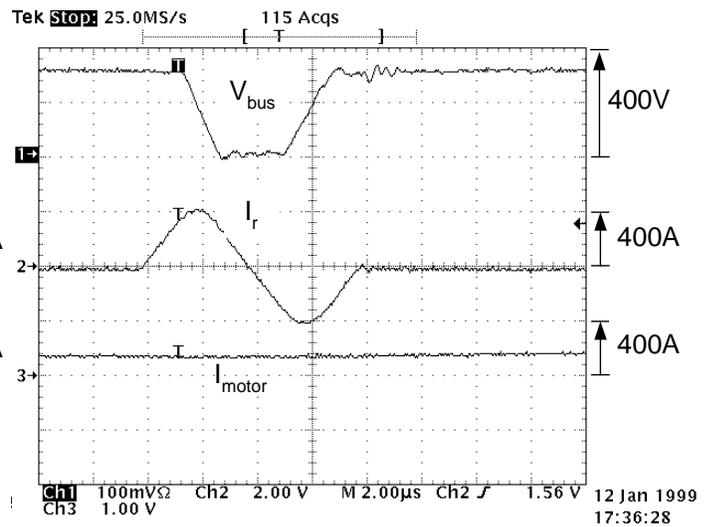Fig. 7. Inverter and motor waveforms.

Fig. 8. Zoom-up of Fig. 7 showing how the resonant current produces a notched dc bus voltage –a zero voltage interval.
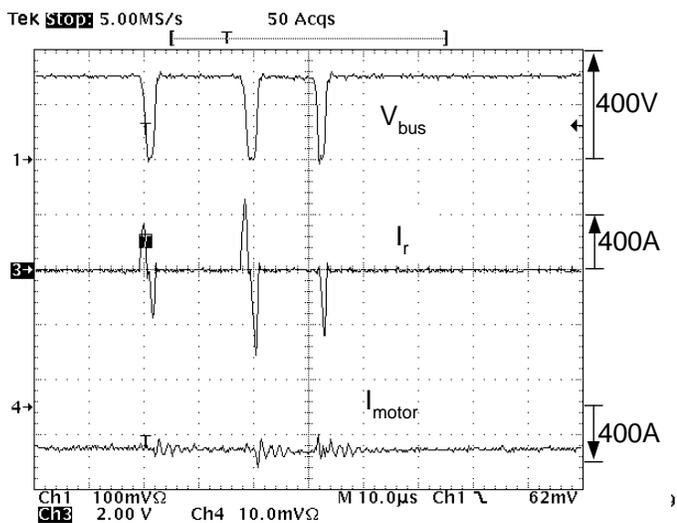

Fig. 9. Zoom-up of Fig. 7 showing resonant current pulses, the amplitude of which is dependent up the initial tank current.
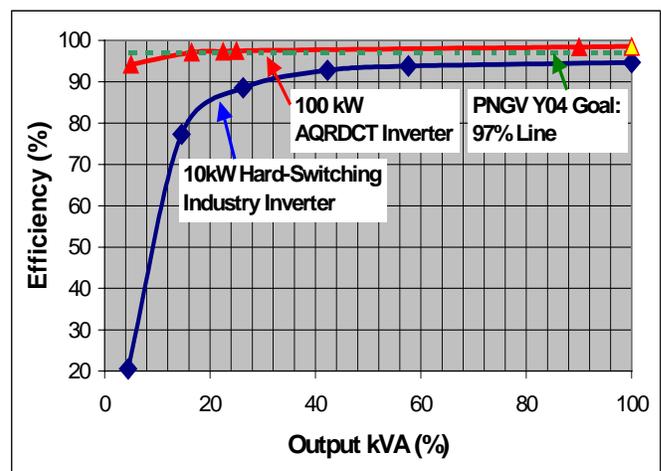

Fig. 10. Measured AQRDCT inverter efficiency.

relatively high tank current *Io* initially flows in clamping switch *Sap*, there is no need to gate on auxiliary switching device *San*. Therefore, no positive resonant current pulse is generated in the third switching instant as shown in Fig. 9. In this way, the resonant current can be minimized and efficiency can be further improved. In Figs. 7, 8 and 9, the motor current, *Imotor*, is also shown. Fig. 10 shows the measured efficiency of the inverter. A typical 10 kW industry hard-switching inverter's efficiency is shown for reference purpose because that was the only data available to the authors.

IV. CONCLUSIONS

This paper has presented a quasi-resonant tank inverter as a new soft-switching alternative. A 100 kW prototype has been built and put into a real electric bus for traction drive. Extensive road tests have shown good reliability, high efficiency, low EMI, and many other new features such as the almost constant dc supply current. In the electric bus the dc supply current is the battery current. This constant dc battery current is very friendly to the battery and reduces battery temperature rise, thus extending battery lifetime tremendously.

References

[1]. D. M. Divan, "Static Power Conversion Method and Apparatus Having Essentially Zero Switching Losses and Clamped Voltage Levels," U.S. Pat. No. 4,864,483, issued Sept. 5, 1989.

[2]. R. W. A. A. DeDonker and J. P. Lyons, "Auxiliary Quasi-Resonant DC Link Inverter," U.S. Pat. No. 5,172,309, issued Dec. 15, 1992.

[3]. H. K. Lauw and R. S. Zedwick, "Voltage Clamped Parallel Resonant Inverter with Controllable Duty Cycle," U.S. Pat. No. 5,559,685, issued Sep. 24, 1996.

[4]. D. M. Divan and G. Venkataramanan, "Comparative Evaluation of Soft Switching Inverter Topologies," EPE Firenze, 1991.

[5]. T. A. Lipo and D. M. Divan, "Resonant Links: A New Family of Inverter Topologies for Solid State Power Conversion," ABB Symposium on Power Semiconductor Devices and Circuits. Sep. 26-27, 1991.

[6]. J. S. Lai and B. K. Bose, "An Improved Resonant DC Link Inverter for Induction Motor Drives," IEEE/IAS Annual Meeting, 1988, pp. 742-758.

[7]. T. G. Habetler and D. M. Divan, "Performance Characterization of a New Discrete Pulse Modulated Current Regulator," IEEE/IAS Annual Meeting, 1988, pp. 395-405.

[8]. H. Mao, F. C. Lee, X. Zhou, and D. Borojevic, "Improved Zero-Current Transition Inverter for High Power Applications," IEEE/IAS Annual Meeting 1996, pp. 1145-1152.