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An improved topology for high power soft-switched power converters

Fred Engelkemeir[a,*], Angelo Gattozzi[b], Gary Hallock[a], Robert Hebner[b]

[a] Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78701, USA
[b] Center for Electromechanics, The University of Texas at Austin, Austin, TX 78712, USA

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ABSTRACT

The push to higher switching frequencies and a desire for lower losses in high power converters requires that switching losses be significantly reduced. Resonant, soft-switching technologies such as the ARCP (Auxiliary Resonant Commutated Pole) attempt to minimize power converter losses by switching the semiconductors at zero voltage or zero current. Deficiencies, however, exist in current ARCP topologies. A novel configuration has been demonstrated that achieves better performance than a conventional ARCP while maintaining essentially the same efficiency and nearly the same power density. This paper describes our new approach and gives simulation and experimental results. A 10 kW, 3-phase inverter, used primarily for driving induction motors, has been constructed and used to experimentally verify the concept.

1. Introduction

With the growth of dc sources such as solar panels, batteries, and dc loads such as electronics and LED lighting, power systems increasingly are incorporating combined ac and dc operation. This is increasingly true in microgrids. High power converters are the components that permit seamless flows of power between ac and dc power systems.

While these components are commercially available there is room to make them smaller, more efficient and less costly. An approach to smaller converters is to operate them at as high a switching frequency as possible since this allows the reduction in the size of reactive components (inductors and capacitors) and of driven electrical machines, and would impact favorably the power quality of the converter's output. However, these benefits cannot always be realized as converter operation at high frequencies is limited by the ensuing higher losses in the IGBT switches used in their power bridge section, which reduces efficiency. IGBT losses have been investigated in depth and significant information is available in reference articles [1,2] as well as from the websites of the major IGBT manufacturers (e.g. [3–5]).

IGBT losses can be separated into conduction losses, present while the device carries the load current, and switching losses, which occur during ON/OFF state transitions of the device. As the frequency of operation increases, the relative weight of these two components of losses in an IGBT changes markedly. Since the switch transition times are rather fixed by the IGBT design and unaffected by a change in switching frequency, as the switching frequency increases the loss distribution is skewed more and more toward a preponderance of switching losses over conduction losses. This is due to the fact that the conduction time is reduced and becomes a smaller fraction of the whole. Therefore, switching losses in the semiconductors that operate large converters can be a significant fraction of the total losses, and can in fact be the dominant loss (80–90%) at the higher frequencies envisioned for future systems. This can be appreciated quickly by using the loss estimator provided by IGBT manufacturers (e.g. on the websites cited above) for the design of a specific converter.

A recognized path to minimize these difficulties is through the implementation of soft-switching technologies. This approach attempts to minimize losses by switching the power semiconductors at nearly zero voltage or zero current, which would indeed result, in the ideal case, in zero switching losses. Minimizing these losses is important because even small efficiency gains can be extremely important in high power (megawatt) converters, and can substantially reduce cooling requirements, component size, and cost.

One design concept for a soft-switched converter and probably the leading option for dc-ac conversion is the one based on the Auxiliary Resonant Commutated Pole (ARCP) configuration. Despite having been introduced nearly thirty years ago [6], ARCP converters have not met with commercial success and no converters of this type are being manufactured in commercial quantities. This seems to be the case for soft-switched converters in general in the MW power range. This is likely due to:

* Corresponding author.
E-mail addresses: engelkemeir@gmail.com, engelk@arlut.utexas.edu (F. Engelkemeir), a.gattozzi@cem.utexas.edu (A. Gattozzi), hallock@ece.utexas.edu (G. Hallock), r.hebner@cem.utexas.edu (R. Hebner).

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- Increased complexity and cost of soft-switched designs.
- Limited market share for applications requiring high performance.
- The expectation that the introduction of wide band gap semiconductor technology, particularly the one based on Silicon-Carbide (SiC) will soon resolve the problem making switching losses smaller so device switching speed can increase significantly.

For the specific case of ARCP designs, there is a fourth important reason, namely some technical problems inherent in the standard ARCP topology. These technical difficulties that resulted in a significant limitation of the output power of the standard ARCP converters are believed by the authors to be a significant contributor to this lack of success in the market-place. With a product that worked reliably only at power levels less than its potential, the higher cost of the ARCP design with respect to hard-switched converters became a moot point; even if it could perhaps be more than justified by the projected enhanced performance.

This paper presents a modification of the conventional ARCP-type soft switching converter. It is intended to be a step toward a more useful embodiment of the technology to help make the concept practical. The ARCP converter has been studied theoretically and experimentally at The University of Texas for the last ten years [7] using a 2 MW ARCP converter unit and a 10 kW version for experimental purposes. This paper is a culmination of this effort and is a significant expansion of our work to improve ARCP performance as initially reported in its principles in [8] and with preliminary experimental results in [9].

A further aim of this research is to investigate the possibility of minimizing switching losses remaining within the silicon-based switching device technology that is used in nearly all of today's commercially available units.

While a potential alternative exists using SiC-based switching devices, these devices are just becoming available in limited selection and have not yet been deployed in any significant number. Due to the limited field experience, the overall system benefits accruing from the use of SiC still need to be quantified. In addition, their high cost remains a possible obstacle to their widespread use for the foreseeable future, making a solution with well proven silicon technology of interest at least in the more general applications.

2. ARCP evolution

The standard ARCP converter was invented by DeDoncker and Lyons [6], and was based on an earlier converter designed to operate using thyristors. The schematic of a three-phase standard ARCP with a motor load is shown in Fig. 1. It is derived from a standard hard-switching inverter, but with some modifications. First, resonant capacitors are placed in parallel with the main switches. These are similar to

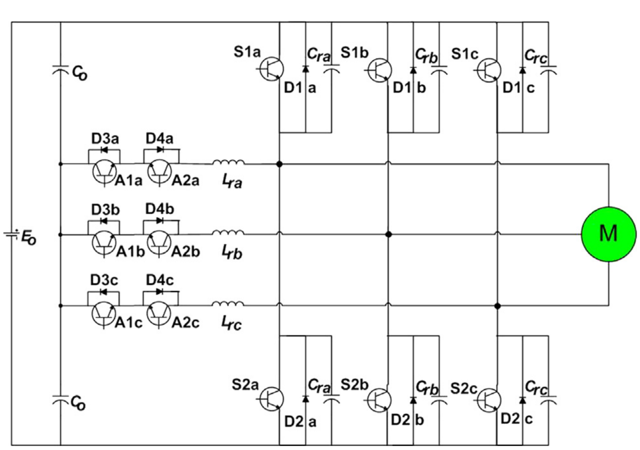

Fig. 1. The standard ARCP (three identical independent phases shown).

snubber capacitors on a hard-switched inverter, but have significantly higher capacitance. Their value is selected to limit the voltage slew rate, allowing the main switches to be turned off at essentially zero voltage.

Second, an auxiliary circuit, comprised of two transistors and an inductor per phase is added to the power circuit. The back-to-back transistors in the auxiliary are used as bidirectional switches. The auxiliary circuit is only used when the output is required to commutate from one voltage rail to the other. It functions by creating a pulse of current that, in combination with the resonant capacitors, is used to slew the voltage on the output node. The transistors in the auxiliary circuit are turned on and off in a soft-switching manner at nearly zero current. The commutation sequence for the standard ARCP converter is well described in the literature [6]. The third modification consists in splitting the dc bus in two by using two equal bus capacitors to provide a virtual neutral point to which the auxiliary circuit is connected.

One of the most problematic issues with the standard ARCP topology is, in fact, precisely the need for a center-tapped dc bus provided by the capacitive voltage divider, as shown in Fig. 1. The voltage balance of the two capacitors must be maintained, with additional circuitry and with an intelligent gating control algorithm. Although conceptually simple, the capacitor voltage balance is difficult to accomplish in practice and introduces an additional loss component in the converter. In the 2 MW standard ARCP converter used in this work, the capacitor balancing circuit occupied approximately 20% of the total converter volume[7,10,11].

A second drawback of the standard ARCP is that the auxiliary circuit has a diode in series with the inductor. The auxiliary current always flows through a diode (the anti-parallel diode of the non-conducting transistor) as well as the transistor which is switched on (the diode is normally a part of the IGBT module). The diode continues to conduct for a short time after the voltage across it has reversed, but then rapidly cuts off conduction. This leads to a large di/dt, which causes the inductor that carries the same current to generate a voltage spike across the auxiliary switches. This can lead to switch failure [12] and results, in practice, in setting a limit to the maximum auxiliary current that can be carried safely. Of course, this also results in limiting the output power of the converter to a value smaller than theoretically possible based on the rating of the power switches.

The standard ARCP topology has been investigated at length at the University of Texas and elsewhere and its shortcomings reported [7,10,13]. Analytical and experimental work on ARCP systems up to 2 MW at the University of Texas have led to two new concepts that address the performance limitations of the original configuration mentioned above. These two new concepts were first introduced theoretically in [8], where they were referred to as #1 and #2, and later tested experimentally with preliminary data reported in [9]. Since then, further tests have been run on all four possible converter configurations, namely hard-switched, standard ARCP, new ARCP #1, and new ARCP #2. The various tests were consistent and repeatable and confirmed the preliminary results reported in [9]. This research demonstrates that:

- The technical problems mentioned previously, and inherent to the standard ARCP topology, have been overcome in both new concepts #1 and #2. Both of these new topologies allow the ARCP to function in load regimes where the standard ARCP would fail.
- New ARCP concept #1 has higher power density than the standard ARCP but lower efficiency.
- New ARCP concept #2 has the same efficiency as the standard ARCP but a lower power density.

Since high efficiency was the main goal of our work, we focused our efforts in further defining the characteristics of new ARCP concept #2, which will simply be called herein the new ARCP. As mentioned, the new ARCP maintains the efficiency achievable by the standard ARCP but resolves some of its technical limitations. In this paper we describe

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