# AN ASSESSMENT OF CELLULAR ARCHITECTURES FOR LARGE CONVERTER SYSTEMS

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Abstract. The concept of cellular power electronic architectures is discussed, in which large numbers of autonomous cells designed for a fraction of the system rating are paralleled. Challenges in designing practical cellular architectures are described, and approaches for meeting these challenges are considered. We present models for thermal management and reliability for cellular systems, along with simulation examples for a recently developed cellular architecture. It is concluded that this approach has potential for improvements in functional performance, reliability, and cost compared to conventionally designed and constructed systems, and should be pursued aggressively.

Keywords: Cellular Power Converters, Parallel Converters, Reliability, Manufacturing, Parallel Resonant Pole Inverter

## INTRODUCTION

Power electronic technology plays an important role in many energy conversion applications, including machine drives, power supplies, frequency changers, and UPS systems. Increases in performance and reductions in cost have been achieved through the development of higher power, fully controllable semiconductor devices, such as the GTO, power MOSFET, and IGBT, and integrated control devices with increased functionality, such as microcontrollers and integrated analog circuits. Manufacturing techniques, however, have changed little. High power is typically achieved by paralleling multiple die in a single package, producing the physical equivalent of a single large device. Consequently, both the device package and the converter in which the device is used continue to require large, complex mechanical structures and relatively sophisticated heat transfer systems.

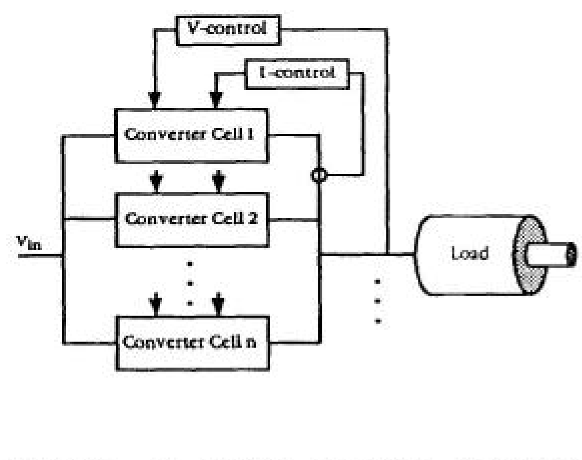


**Figure 1** A cellular converter architecture supplying a single load.

An alternative to this approach is the use of a cellular architecture (1). As shown in Fig. 1, a cellular architecture is based upon the parallel connection of a large number (> 10) of autonomous converters, called cells, each designed for a fraction of the system rating. The cell rating, typically on the order of 3-5 kW, is chosen such that single-die devices in inexpensive packages can be used and the cell fabricated with an automated assembly process. The use of autonomous cells means that system performance is not compromised by the failure of a cell.

Paralleled converter systems are often used when very high power levels are required (2),(3), as well as in applications demanding high reliability (4). However, paralleling on a scale discussed in this paper, where mass production techniques can be used, remains largely unexploited. We anticipate that systems built using a cellular architecture can exhibit improved functional performance, improved maintainability and reliability, and reduced cost when compared to systems designed and constructed in a conventional manner. This paper investigates the cellular architecture concept, and outlines some of the challenges to, and approaches for, bringing it to commercial viability.

## PERFORMANCE ASPECTS

The cellular architecture's potential for improved functional performance arises from the characteristics of both the individual cells and their aggregation. At the cell level, the smaller components and physical dimensions of interconnects make possible an appreciable increase in switching frequency. The power processing capability of system components such as devices, capacitors, etc, is directly related to their volume. As the size and spacing of these components become larger, so do the parasitic elements which limit performance. For example, a typical plastic-packaged 40A 600V IGBT may have a package inductance on the order of 10 nH, while a 400A 600V IGBT module may have an inductance on the order of 30 nH. Because switching losses due to this parasitic inductance are proportional to frequency and the sum of $Li^2$ terms, the small devices have considerable advantage as the switching frequency is increased. Similarly, lead inductance values make it far easier to select and connect resonant or snubber capacitors for multiple small devices than for a single large module, especially if high speed devices are being used. Thus, the physical dimensions of the components and interconnects heavily favor a cellular architecture when high switching frequencies are desired.

The aggregation of outputs of many cells also yields significant performance advantages over a single large converter. The advantages of *interleaving*, in which multiple converters are operated out of phase, are well known (5),(6). Paralleled converters which are controlled autonomously also possess advantages over the single converter alternative. Because they are controlled autonomously, the cells exhibit neither frequency nor phase coherence. Thus, their aggregated outputs produce a low energy density spectrum with stochastically reduced harmonic components. The effects of aggregation make possible considerable reductions in both acoustic noise (for loads such as machines) and EMI.

An example of a cell topology in which the aggregation of autonomous converter outputs can reduce undesired output components is the Parallel Resonant Pole Inverter (PRPI), shown in the single-phase half-bridge configuration in Fig.

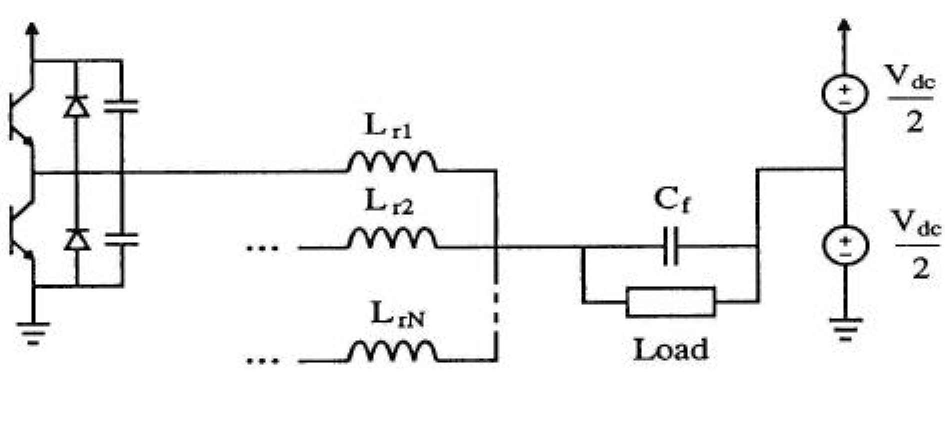


**Figure 2** The Parallel Resonant Pole Inverter architecture (PRPI).

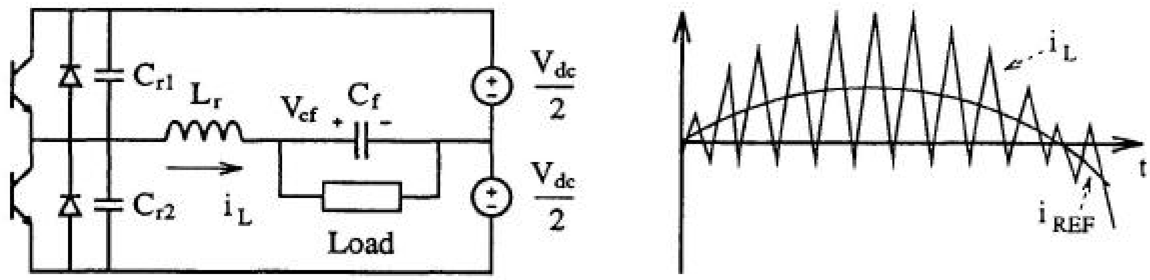


**Figure 3** The Resonant Pole Inverter and its operating waveforms.

2. This converter structure, introduced in (7) and described in Appendix A, is based on the Resonant Pole Inverter topology (8),(9). It is well suited to the parallel architecture because of its simplicity, small passive component size, and ability to operate at high switching frequencies.

The free running PWM of the single resonant pole inverter of Fig. 3 generates significant rms current ripple in the output filter capacitor. This rms current ripple increases the size and cost of the required filter capacitor, and is one of the most objectionable characteristics of the resonant pole inverter (10). As discussed in (7), and shown in Fig. 4, an equivalent *N*-cell Parallel Resonant Pole Inverter (PRPI) can be formed, which to first order has the same cell operating frequency, total energy storage and power dissipation as the single RPI. However, as can be inferred from the simulation plots of Fig. 5, a 10 cell PRPI has far less voltage ripple than the single RPI due to aggregation of the cell outputs. Furthermore, for the particular example shown, the RMS filter capacitor current in the PRPI is reduced by over 70% from the current in the RPI, considerably reducing stresses and losses, and allowing the use of a physically smaller, less expensive output filter. Note that while the switching frequencies of the cells were assumed to be the same as that of the single converter for this comparison, in practice the cell frequency can be made higher. Thus, both the increase in switching frequency and the aggregation of outputs available in a cellular architecture make it advantageous compared to the single converter alternative.

## RELIABILITY

System reliability is determined by both component reliability and the results of component failure. Component reliability in a cellular system can be higher than in conventional systems for a number of reasons. First, automated assembly and test is known to produce more consistent and higher quality products than manual assembly. Second, many of the components, such as the semiconductor devices, are produced in high volume and are therefore better characterized than their larger, more complex counterparts in conventional systems. Finally, because its higher switching frequency results in a higher control bandwidth, a cellular system can respond more quickly to abnormal and damaging system conditions, such as short circuits and overloads.

Nevertheless, the fact that a cellular system has more components must be addressed when considering the system reliability. High system reliability can be achieved by incorporating more cells than necessary to meet the required power rating, thus exploiting the inherent redundancy of the architecture.

Appreciation for the trade-offs among net component count, redundancy and reliability, can be obtained using relatively simple models. Consider a model which predicts the reliability of a $(K,N)$ parallel converter system over some defined operating lifetime. A $(K,N)$ converter system is one with $N$ total cells, where $K$ cells are required to meet 100% rated capacity (a conventional converter is thus a (1,1) system). Reliability is defined as the probability that the number of operational cells will not fall below $K$.

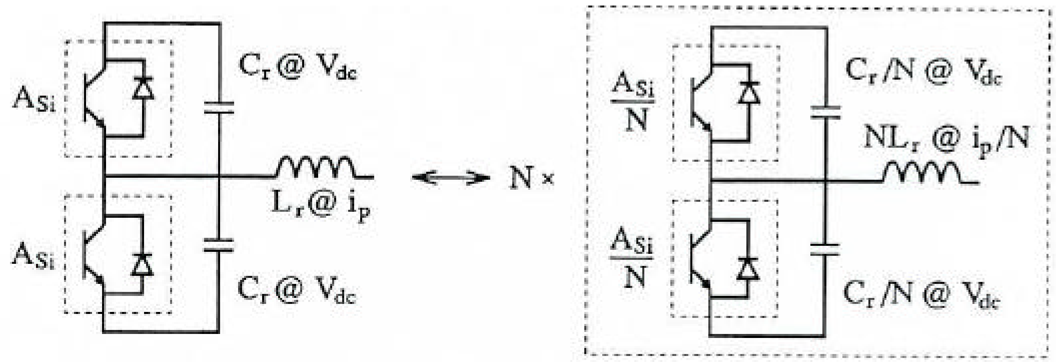


**Figure 4** A Resonant Pole Inverter leg and its equivalent Parallel Resonant Pole components.

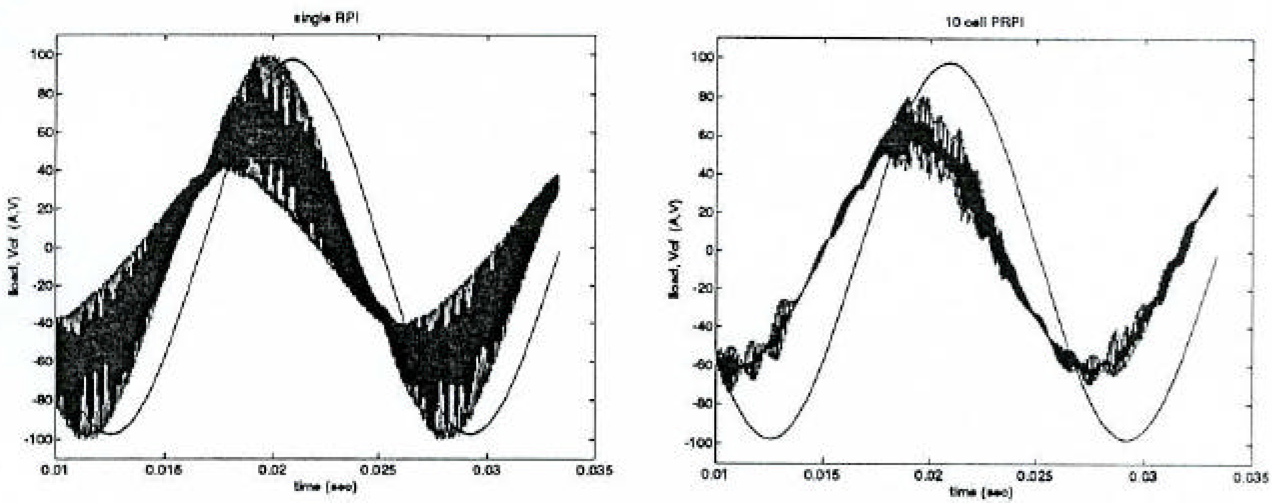


**Figure 5** Simulation of an RPI and an equivalent ten cell PRPI. Single RPI has $V_{dc}$ = 300 V, $L_r$ = 25$\mu$H, $C_r$ = 0.16 $\mu$F, $C_f$ = 50 $\mu$F, $L$ = 1 mH, $R_l$ = 0.5 Ω.

We model the probability of failure of individual cells during the operating lifetime as independent Bernoulli trials, with probability of failure $P_f$. The reliability of the ($K$,$N$) system over its operating lifetime is thus (11):

$$R = \sum_{i=K}^{N} \binom{N}{i} \left[ 1 - P_f \right]^{i} P_f^{N-i} . \qquad (1)$$

Figure 6 shows the reliability of a system with 50 cells for three different values of cell reliability (1-$P_f$). As can be seen, for a 50 cell system with relatively reliable cells, the redundancy needed to meet and exceed the reliability of a single converter system, (1-$P_f$), is modest, 6.4% for $P_f$ = 0.01. That is, the reliability of a (47,50) cellular system (0.9984) exceeds that of a single converter (0.99). However, as the individual cell reliability declines, the redundancy required to attain the same reliability as a single converter is much higher. In the likely event that the individual cells are more reliable than the single large converter (due to the different component

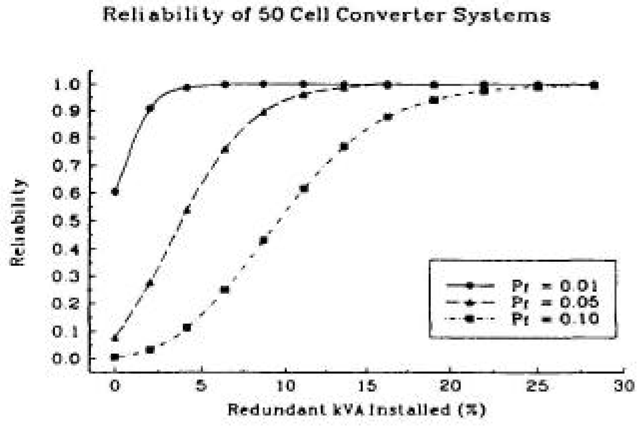


**Figure 6** The reliability of a 50 cell converter for three cell failure probabilities.

attributes, assembly processes, testing, etc), the cellular architecture becomes even more attractive.

Other reliability benefits of the cellular approach are not captured by this simple model. For example, with a cellular architecture, it is possible to design systems which are *gracefully degrading*. That is, a cellular converter can continue to function at reduced rating even after the number of cell failures exceeds *N-K*. In contrast, a conventional system could not operate at reduced rating- it can either supply the rated load, or it cannot supply any load. Furthermore, most large converter systems are designed to support some percentage of continuous overload, so that the redundant units in a cellular system may not represent any excess installed kVA at all.

Another aspect of reliability which is of interest in many applications is availability. Availability is defined as the fraction of time the converter is expected to be operational (for our purposes, at 100% rated capacity). To model the availability of conventional and cellular converters, we will assume independent, exponentially distributed time periods for failure and (one at a time) repair of individual converter cells. We can then construct a simple Markov chain model, as shown in Fig. 7, which probabalistically describes the evolution of the system operating condition based on cell failure rate $\lambda$, repair rate $\mu$, and the current state of the system. We use this model to compute the steady-state probability that any number of converters in a $(K,N)$ system will be operational, and hence find the availability of the system (12). Consider the availability of a single converter using this model. If we use a Mean Time Between Failure (MTBF, $1/\lambda$) figure of 2 years, and an Mean Time To Repair (MTTR, $1/\mu$) of 185 hours as suggested by the range of values in (13),(14), we find that the availability of the system is 0.9895. Now consider the availability of a (45,50) cellular converter system. Using the same MTBF and MTTR values for the individual cells, we get a slightly lower availability of 0.9523. However, consider reducing the MTTR parameter of the cellular converter to 24 Hours. This is perfectly reasonable, since repairing a cellular architecture involves only replacing a single standard cell, and does not require the special labor and parts needed to repair a conventionally constructed converter. With these parameters, the availability of the cellular system is 0.999999924 - vastly superior to the conventional alternative. In fact, a more realistic model allowing multiple failed units to be repaired in parallel would favor the cellular converter even more heavily.

These simple arguments indicate that it is quite

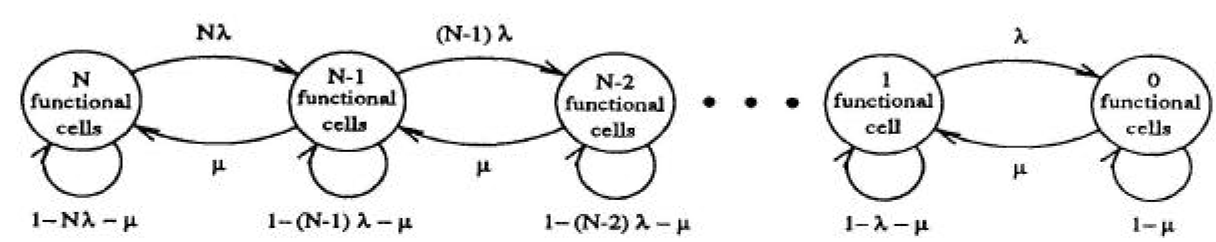


**Figure 7** A Markov chain model for cellular converter availability calculations.

possible for the reliability of a cellular converter to far exceed that of the conventionally constructed alternative. To realize these potential benefits, methods must be developed to eliminate single-point failure modes in the distributed system so that the failure of a single converter cell does not cause a system failure.

## COST ISSUES

The penetration of power electronics into energy conversion applications has been driven primarily by economics and secondarily by performance. Thus, in all except for the few applications where reliability or performance are of primary importance, the success of cellular architectures in the marketplace will depend on economics.

### Assembly and Test

One area in which cellular architectures have cost benefits is in the assembly and test process. Hand assembly and test is the standard method for constructing high power converter units. This process is both costly and complex. Conversely, automated assembly equipment can be used to manufacture and test the cells in a cellular architecture, reducing the hand assembly portions to a minimum and eliminating much of the more complex work. Furthermore, because large numbers of identical cells can be built (even for constructing converters of different ratings), economies of volume can reduce costs.

### Thermal Management

A second area in which a cellular system has economic advantages is in the cost of the thermal management system. At low power densities, inexpensive air-cooled extruded or bonded-fin heat sinks can be used for cooling. For higher power densities, much more expensive liquid cooling technologies must be employed. The thermal power density through the contact surfaces of plastic-packaged devices and large power modules are both in the same range (roughly 50-200 W/in$^2$). However, because a particular device can only transfer heat effectively through a limited surrounding heat sink area, the relative position of heat sources (devices) on the sink is important. By distributing the heat sources, a cellular architecture can take advantage of heat sink area much more effectively than can a single power module, leading to a lower *effective* power density for the distributed system.

To understand this quantitatively, we construct thermal models for single-module and distributed systems, as shown in Fig. 8. For devices with a constant on-state voltage (such as IGBTs), the junction-to-case thermal resistance ($R_{jc}$) of a plastic packaged device rated for $I_o$ amperes will be roughly $N$ times that of a module rated for $NI_o$ amperes. This follows directly from the fact that the power handling capability of a package is thermally limited. The scaling of contact surface changes $R_{cs}$ in a similar manner. Next, consider the thermal resistance of the heat sink. The sink-to-ambient thermal resistance ($R_{sa}$) of an air-cooled heat sink for a point-source of heat initially decreases with increasing sink size. However, as shown in Appendix B, the thermal resistance stops decreasing as the size of the heat sink becomes larger because sections of the heat sink far from the point-source do not contribute to the heat transfer. Thus, to first order, there is a minimum $R_{sa}$ that can be obtained for a given heat sink with a point-source load, which can typically be determined from manufacturer's derating tables. Now, if we divide the single point-source into $N$ point-sources, we can obtain the same minimum thermal resistance *from each point source*. Applying these concepts, we obtain the thermal models of Fig. 8. As can be seen, distributing the single point source of heat can yield dramatically lower junction temperatures for the same total power dissipation, due to improved utilization of the heat sink. Practically speaking, this allows a cellular converter to use a lower power density, lower cost thermal management system than a conventionally constructed converter.

### Control Circuits

While high volume and automated assembly surely reduce costs, as does the simplification of thermal management possible in a distributed system, there are several aspects of the cellular approach which increase cost. Some components in a cellular converter can be seen as a redistribution of the component parts of a single large converter, as illustrated in Fig. 4. However, some circuit components, such as sensing and control circuits, are not distributed among converters, but are replicated. As more and more cells are used, the replicated component costs become a higher fraction of the total, and degrade the economic benefits of the cellular approach (although this is partially offset by the ability to attain higher levels of integration of these components). The ultimate economic benefits of the cellular approach thus remain uncertain. It is likely, however, that the optimal cost point for the approach comes when the cells are sized to allow automated assembly at the pc board level, but no smaller.

## DESIGN CHALLENGES

To fully realize the benefits of cellular conversion, design approaches suited to this architecture must be developed. One critical aspect of a cellular architecture is the need for a current sharing mechanism to prevent the destructive overload of individual cells. Typically, current sharing in a parallel system is achieved through the use of an appropriate magnetic structure to make the individual converters act as current sources for times on the order of the switching period. Many magnetic structure design possibilities exist, including interphase transformers, dc or resonant current links, and output inductors. For all approaches, minimization of the energy storage requirement of the current sharing mechanism is an important design objective, since it can represent a significant fraction of converter size and cost.

Simplicity of sensing and control is another desirable feature of a practical cell architecture, since circuits for these functions have a large cost impact. Current sensing is required in many design approaches, and can represent an appreciable cost constraint. Power stage topologies which do not require current sensing, such as some resonant techniques, may thus have some advantage for this application.

Similarly, power stage topologies which offer very simple control and failure detection are advantageous. The design of the overall control system is a crucial issue, since it heavily impacts the cost, reliability and performance of the resulting architecture. For some applications, such as uninterruptible power supplies, it is quite possible to develop control schemes for paralleled converters in which there is no information transfer among cells (15). This type of approach may yield the best reliability in applications where it can be used, though the cost impact of the local controllers may be severe.

Another option is to have only minimal information transfer among cells, such as reference or timing information, implemented in a failsafe manner. Many interesting opportunities exist for this approach. For example, local controllers could be designed to tune themselves (on a slow time scale) for optimal performance in a system with an unknown (and possibly time-varying) number of cells. It may also be possible for individual converters to perform ripple cancellation on the aggregate output using only locally measurable quantities, thus attaining higher output quality.

At the other end of the spectrum is the possibility of using redundant high-level supervisory controllers, leaving the individual cells to only manage gating and fault handling. This approach can probably attain the highest performance because of the possibility of active interleaving. However, it may have a severe impact on overall reliability due to the large number of interconnections and possibilities for single-point failure modes.

Ultimately, any suitable design approach must achieve a balance between performance, reliability, and cost. One example of a suitable power stage topology is the Parallel Resonant Pole

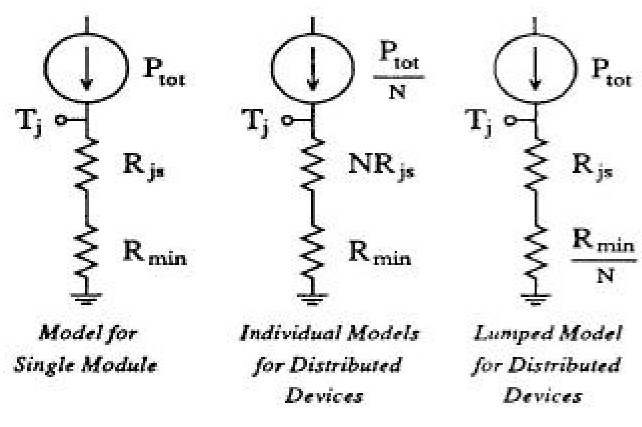


**Figure 8** Thermal models for modules and distributed discrete devices.

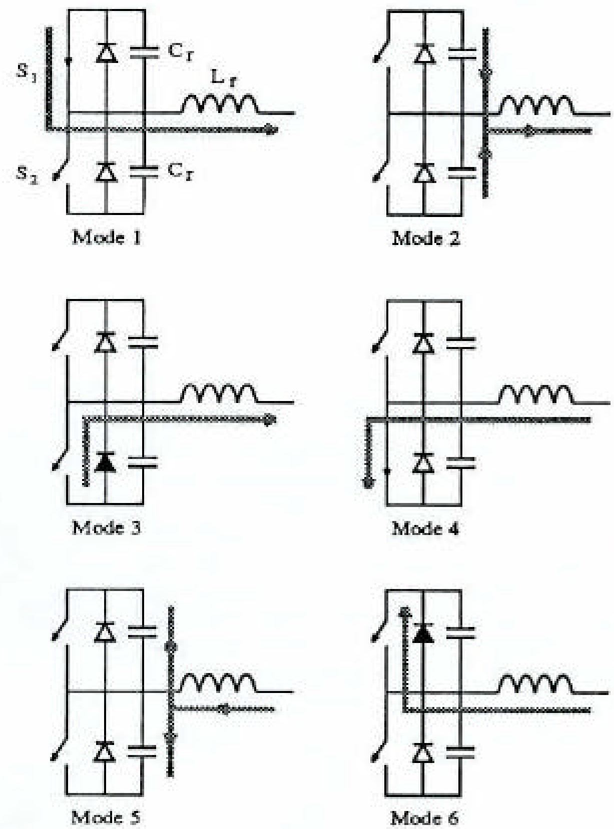


**Figure 9** An operational cycle of the Resonant Pole Inverter.

Inverter (PRPI), shown in Fig. 2 and currently under development at MIT. This topology exhibits many of the desired characteristics. The use of small resonant output inductors in each cell achieves a minimally-sized current sharing mechanism, while providing full soft switching of all devices. The autonomous free-running PWM control is simple, robust and inexpensive to implement, and can be used with either completely autonomous or reference-sharing global control schemes. While this approach is by no means the only viable one for cellular architectures, it represents a good baseline topology.

## CONCLUSION

The concept of cellular power electronics architectures has been discussed, in which autonomous cells designed for a fraction of the system rating are paralleled. We have shown that this approach has the potential for improved functional performance, reliability, and cost compared to conventionally designed and constructed systems. We have also outlined some of the challenges in designing practical cellular architectures, and described some approaches for meeting these challenges. Taken together, the previous discussions argue compellingly that this type of power converter architecture should be pursued aggressively.

## APPENDIX A

To understand the PRPI architecture, consider the single Resonant Pole Inverter (RPI) shown in Fig. 3. An operational cycle of the resonant pole inverter is shown in Fig. 9, and is described as follows: Assume that the output filter capacitor is large enough to clamp the voltage for the duration of the cycle, and that operation begins with $S_1$ conducting (Mode 1). The resonant inductor current builds up linearly, until it hits a current $i_{p+}$ specified by the controller. At this point, $S_1$ is turned off at zero voltage, and $L_r$ rings with the two resonant capacitors (mode 2) until $D_2$ conducts (Mode 3). During conduction of $D_2$, $S_2$ is turned on at zero voltage, while the current in $L_r$ linearly decreases and reverses (Mode 4). When the reverse current reaches a level $i_{p-}$ specified by the controller, $S_2$ is turned off at zero voltage, and the voltage bus rings up (Mode 5) until $D_1$ conducts (Mode 6). $S_1$ can then be turned on again allowing the cycle to repeat. A desired average reference current $i_{REF}$ is generated by controlling the values of $i_{p+}$ and $i_{p-}$, which are also constrained by the necessity of having enough energy in the resonant inductor to ring the bus for zero-voltage switching. The conventional control algorithm for doing this is shown in Table 1, where we define:

$$i_{\min} = 2\sqrt{\frac{C_r V_{dc} |V_{cf}|}{L_r}} \qquad (2)$$

An enhanced control algorithm which significantly reduces converter losses for many operating conditions was introduced in (7), and is shown in table 2. The behavior of the Parallel Resonant

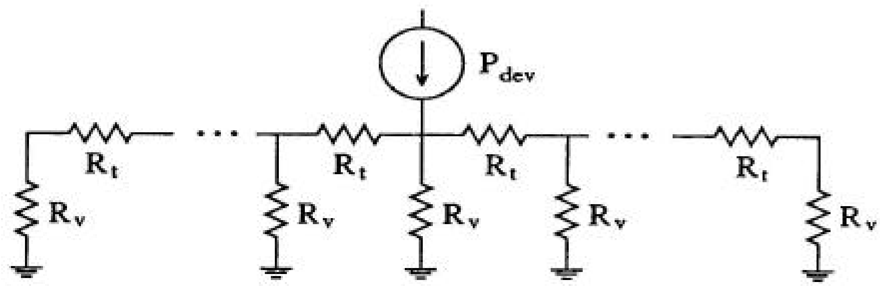


**Figure 10** Model for calculating minimum effective thermal resistance for a convection-cooled heat sink.

Pole Inverter is determined as the aggregate of many individual RPI cells operating into a common load.

## Appendix B

To understand why the point-source thermal resistance of a convection-cooled heat sink does not decrease indefinitely as heat sink size increases, consider the one-dimensional, lumped parameter model of Fig. 10. The heat sink is divided into lateral segments of a specified width. The resistor $R_v$ models the effective sink to ambient thermal resistance of a given segment, while $R_t$ models the transverse thermal resistance to heat flow between segments. Numerical values for these parameters are a function of heat sink dimensions and material properties, and can be determined from manufacturer's data sheets. The Thevenin resistance of the ladder to the heat source is a function of the length of the heat sink. Figure 11 shows the thermal resistance predicted by this model for a typical convection-cooled heat sink. As can be seen, there are severely diminishing returns for increasing heat sink area beyond a certain point. In fact, because the cooler parts of the heat sink do not transfer heat to the air as efficiently, the minimum effective thermal resistance is even higher than predicted by this simple model. Ultimately, then, there is a minimum thermal resistance to a point-source load that can be attained with a given convection cooled heat sink, regardless of length used.

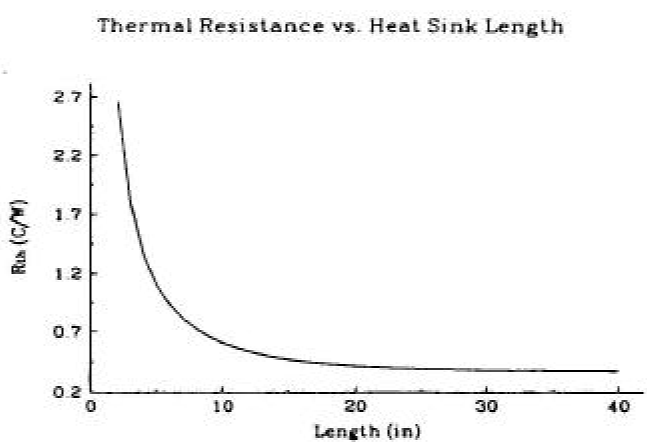


**Figure 11** $R_{th}$ as a function of length for a typical (4.9 in. wide) heat sink.

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**Tables 1,2 Parallel Resonant Pole Inverter control tables.**

| $i_{ref}$ | $<0$ | $>0$ |
|---|---|---|
| | $i_{p+} = i_z$<br>$i_{p-} = 2i_{ref} - i_z$<br>$i_z = i_m$ | $i_{p+} = 2i_{ref} + i_z$<br>$i_{p-} = - i_z$<br>$i_z = i_m$ |

Table 1

| $V_{ef}$ \ $i_{ref}$ | $<0$ | $>0$ |
|---|---|---|
| $>0$ | $i_{p+} = i_z$<br>$i_{p-} = 2i_{ref} - i_z$<br>$i_z = i_m$ | $i_{p+} = 2i_{ref} + i_z$<br>$i_{p-} = - i_z$<br>$i_z = \max(i_m - 2i_{ref}, 0)$ |
| $<0$ | $i_{p+} = i_z$<br>$i_{p-} = 2i_{ref} - i_z$<br>$i_z = \max(i_m + 2i_{ref}, 0)$ | $i_{p+} = 2i_{ref} + i_z$<br>$i_{p-} = - i_z$<br>$i_z = i_m$ |

Table 2


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