Advanced Power Supplies

Scoping Study and Technology Assessment

TR-110405

Final Report, April1998

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Soft Switching Technologies

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REPORT SUMMARY

This report provides a scoping study and a technology assessment for advanced power supplies in three target markets: residential, commercial, and industrial. The study focuses on two general categories of applications that create additional value for utility end users—on applications where electrotechnologies create opportunity for increased use of electricity or where new processes based on power electronics and electricity can replace traditional methods.

Background
In most residential, commercial, and industrial applications, power delivered to a load is conditioned by a power supply to a useable form. Frequently, the power supply is a key limiter in the overall performance of the end-use application. Until now, there has been no systematic study that has evaluated a wide range of targeted customer applications where power supplies are used or that has identified key areas in which better power supply technology can improve overall system performance and cost.

Objectives
- To evaluate a wide range of residential, commercial, and industrial applications that use power supplies.
- To identify areas where improved power supply technology can enhance system performance and reduce cost.

Approach
The authors review attributes of core power supply technologies and typical end-use applications for these technologies. They also take a detailed look at key technologies in the dc and ac power supply area. After reviewing several examples of end-use applications for power supplies, they perform a market study to prioritize R&D efforts that will have the maximum potential economic impact.

Results
The study highlights the potential for improvements in power supplies and for any resulting improvements in the system's reliability, power quality, and cost. A wide range of power supply solutions for specific applications are covered, many of them already available from several vendors. Other cutting edge technologies that show great promise for the future are described. The study also provides a representative

listing of equipment types, detailing the type of power supply used, technical features, equipment vendors, and costs.

EPRI Perspective

Fairly fragmented at present, the power supply business sector has been unable to move successfully towards advanced technology. Advances in power supply technology could improve overall system efficiency, reducing size and possibly cost. Such advances would benefit many commercial, residential, and industrial end users.

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Interest Category

Power conditioning

Keywords

Advanced power supplies

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INTRODUCTION

This report presents a scoping study as well as a technology assessment for advanced power supplies used in industrial, commercial and residential applications. The study is focused on applications where electro-technologies provide opportunity for increased use of electricity, or where new processes based on power electronics and electricity use can supplant established methods, creating additional value for utility end-use customers. Target customers can be in the residential, commercial and industrial sectors. In most of the targeted applications, the power delivered to the load is conditioned by a power supply to a form which can be usefully utilized. Frequently, the power supply represents a key cost factor, and often is a primary limiter of the performance achievable in the end-use application of process. Identifying where such limits and opportunities exist can open the door to technology advances which benefit the targeted end-user.

The power supply business sector is fairly fragmented at present, and has not been able to systematically consolidate or invest in moving towards advanced technology. As the power supply typically does not constitute a core technology competency for the end-use equipment manufacturer, it typically lags behind in terms of technology level. Advances in technology in the power supply area could improve the efficacy of the process, reduce size, improve efficiency, and possibly reduce cost. There is presently no systematic study which evaluates a wide range of industrial, commercial and residential applications where power supplies are used, and which identifies key areas in which overall system performance and cost can be improved via the use of better power supply technology.

This report presents power supply requirements in various applications including induction cooking, induction heating, metal finishing, ozonation systems, pulse power incinerators and sterlizers, welding, plasma spraying, corrosion protection, precision welding, magnet supplies, induction hardening, anodizing, and other similar areas. The report highlights the potential for improvements in the power supply itself, and for any resulting improvements in the process, in the reliability, power quality and cost of the system. A market study is then used to prioritize R&D efforts in areas of maximum potential economic impact.

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BASIC POWER SUPPLY TECHNOLOGIES

Power supplies used in electro-technology processes in industrial, commercial and residential applications span a wide range from a few tens of watts to tens of megawatts. An ubiquitous application today is that of switched mode power supplies used in personal computers and other office equipment. Another application which has seen very strong growth is that of the uninterruptible power supply industry. Although these applications are strictly electro-technologies, they are not covered in this report, as they have received extensive coverage elsewhere. The report is also not concerned with technologies such as adjustable speed motor drives and other forms of energy conversion, as those do not strictly fall into a pure electro-technology umbrella.

Power supplies can be categorized in several different ways. Of primary importance is the form of the electrical power required for the end process, and the form of the electrical power available at the energy source. This information defines the solutions which are potentially cost effective and commercially viable.

Residential and Commercial Applications:

< 1 kW:	Fluorescent ballast, halide lamps, RF lamps, fast battery chargers, electronic cooling
1kW - 5 kW:	Induction cooking, microwave ovens, clothes dryers
>5kW:	EV chargers (inductive and conductive), back up power sources

Industrial Applications:

<1 kW:	Cathodic protection,
1kW - 5 kW:	Battery formation, electroplating, cathodic protection, telecommunication supplies,
5 kW - 50 kW:	Electroplating, anodizing, ozonation, welding, spot welding, telecommunication supplies, EV chargers,

50 kW - 500 kW: Plasma spraying, EV fast chargers, induction heating, induction hardening, induction welding, X-ray supplies, magnet supplies,

500 kW - 10 MW: Electrowinning, waste incineration, induction melting,

The diverse end-use applications listed above are served by variants of a surprisingly small core of power supply technologies. The type of power supply technology used is governed to a large extent by the type of end-use electrical power required, by the space and cost limitations, and by the period over which the market has been in existence. For instance, in new and emerging end-use markets, the tendency is to use newer technologies, while in established product markets, older technologies dominate and the speed of change is fairly slow.

The following core power supply technology areas can be identified, again by end-use and by power rating. It should be clearly understood that broad variations in actual implementation can occur within each technology area, driven by vendor attempts to meet specific customer needs and to reduce cost. While it is impossible to cover all such variations, an attempt will be made to provide instances where such variations provide unique cost and performance benefits. The core power supply technologies can be broadly defined as shown in Table 2.1, along with their attributes, power ranges and type of power delivered.

Table 2-1
Attributes of Core Power Supply Technologies

Converter Type	Output	Power Range	Advtgs	Disadvtgs
Phase Controlled Rectifier - A	DC	10V - 10 kV 10A - 100 kA to >20 MW	Mature technology Simple converter and control	Bulky Poor power factor Voltage notching
Switched Mode Power Supplies - B Hard Switching	DC	2V - 60 kV to 500A to 20 kW	Small size, high frequency isolation Fast dynamic response Unity displacement factor	Limited in power/current due to thermal issues More expensive solution Higher EMI Regeneration is difficult and expensive
Switched Mode Power Supplies - C Soft Switching	DC	2V - 60 kV to 2000 A to >200 kW	Similar advantages as B Lower cost at higher power/current levels Can achieve higher power/current than B Lower EMI and high efficiency	Newer technology Regeneration is difficult and expensive
High Frequency Inverters - D	High frequency AC	to 600 kW to 500 kHz	Compact solution to high frequency outputs Typically resonant/soft switched for low EMI IGBT/MOSFET solutions are newer technology	Higher cost than thyristor solutions Increases cost to have higher power factor
Low to Medium Frequency Inverters - E	AC	to 1 MW 60 Hz to 10kHz	Mature technology, uses thyristor converters	Poor power factor Bulky
High Current Choppers - F	DC	to 4 MW 10-150 volts 1kA - 100kA	Uses IGBTs with zig-zag transforme High power factor Low harmonics Fast dynamic response	Complex and bulky transformer Not cost competitive unless input line harmonics are included
Other - G	DC and AC		Includes tap changing transformers, linear supplies, ferroresonant voltage regulators, vacuum tube RF amplifiers, and special rotating machines with HF output	Not consistent with power electronics solutions, generally becoming less popular in new equipment

A brief discussion of the basic operating principle for each power converter type is given in Section 3. The core technology information from Table 2.1 can be further correlated with the end use application and power rating. This is shown in Table 2.2.

Table 2-2
Typical End-Use Applications for Power Supplies

Application	Output	<1kW	1-5kW	5-50kW	50-500kW	>500kW
Induction cooking	AC	D	D			
Induction heating	AC	DG	DE	DE	DE	EG
Induction melting	AC				EG	EG
Induction welding	AC					
Induction hardening	AC	D	D	D	D	D
RF heating and curing	AC	D	D	D		
Ozone generation	AC	DG	D			
Fluorescent ballast	AC	DG				
Halide lamps	AC	D				
Battery Chargers	DC	AB	AB	ABC	ABC	
X-Ray, MRI	DC		C	C	C	
Magnet Supplies	DC		AB	AB	AB	
Cathodic Protection	DC	AB	AB	A		
Battery Formation	DC	A	A	A	A	
Telecommunication	DC	BC	BC	BCE	ABCE	
Electroplating	DC	AB	AB	AB	A	AF
Precipitators	DC		A			
Plasma Spraying	DC			A	A	
Welding	DC		ABC	AB		
Waste Incineration	DC				A	

It should be noted that the above list indicates what the present status of technology is in commercially available products, and is not indicative of where opportunities exist for improvement. This also does not give any indication of whether an available technology is cost competitive or is dominant in the existing marketplace. Some of these aspects of individual technologies, their relative advantages and disadvantages, and their relative costs are discussed in the next section.

3

CORE POWER SUPLLY TECHNOLOGIES

The various core power supply technologies have been briefly described in the above section. This section will provide a more detailed discussion of the elements and properties of the various power conversion approaches.

3.1 Phase Controlled Converters (A)

Figure 1 shows a block schematic of a phase controlled converter, normally used to convert incoming ac line voltage into a controlled output dc voltage or current. The system typically consists of a low frequency (60 hertz) input transformer followed by a six thyristor bridge. The thyristor bridge 'rectifies' the incoming line voltage and creates an output voltage which has finite and controlled average (or dc) value, and has an ac voltage at a multiple of the line frequency. For six pulse rectifiers, this frequency is six times the line frequency. Similarly, higher pulse number rectifiers can be obtained with 12, 18 and 24 pulse operation. The rectifier output voltage (dc+ac) is filtered by a output reactor. The ac component of the rectifier output voltage causes ripple current in the output reactor. As the pulse number of the rectifier increases, the ripple current obtained in the output current is reduced for a given size of reactor. Alternatively, the reactor size can be reduced for a given level of filtering as the pulse number is increased. It should also be noted that by using two phase converters in parallel in a dual converter configuration, it is possible to handle bidirectional power flow, and to realize four quadrant operation.

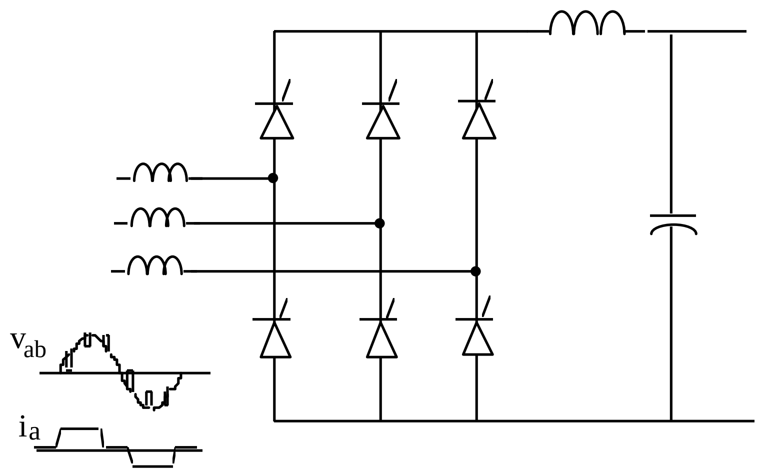

Figure 3-1
Block schematic of a phase controlled converter

On the input line side, phase controlled rectifiers have significant problems. The single biggest problem is the input power factor, which decreases with decreasing output voltage. Another important parameter to monitor is the input VARs consumed by the phase converter. In some applications, it may be possible to compensate total VARs consumed by the system with a single capacitor, while it may need a bank of switched capacitors in other applications. A second issue with phase converters is of harmonics on the line side. Six pulse converters generate harmonic currents at the line frequency (fc), as well as at 5fc, 7fc, 11fc, 13fc, etc. One advantage of converters with higher pulse numbers is a reduction of the low frequency input line current harmonics. Twelve pulse converters, for instance, generate harmonics at 11fc, 13fc, 23fc, 25fc, etc. As the waveforms for six and twelve pulse converters indicate, the higher pulse numbers give waveforms which are visibly more sinusoidal, which is highly desirable. As may be anticipated, higher pulse number rectifiers tend to cost more than six pulse rectifiers, unless low harmonic input currents are an integral part of the system or equipment specification.

One last important issue on the line side is that of voltage notching. As thyristors turn-on and off, there is a resulting period of overlapping conduction, which causes a temporary short circuit between the incoming and outgoing phases locally at the converter input line connection. This deep notch can be 10 to 200 microseconds wide, and can cause significant interference with other equipment, and with power factor correction capacitors in the plant. The problem is somewhat reduced by the use of input reactors and converter transformers.

Cost factors associated with phase converters are well understood, as the technology is mature. Examining the block diagram, it is seen that the heart of the converter is the thyristor bridge and its associated controls. In certain applications, such as dc motor drives, this core (along with application specific controls) can essentially provide a complete solution to the end-use customer. This lowest cost package cannot typically be used for most 'electrotechnology' applications. A typical solution will include an input transformer, the thyristor bridge, associated controls, an output reactor and switchgear, housed inside an appropriate cabinet. Typical best prices for such phase converters are $1500 for a 10 kW supply ($150/kW), $11,000 for 100 kW supply ($110/kW), $80,000 for a 1 MW supply ($80/kW). These are typical prices based on using a very small output filter reactor, and for six pulse rectifiers. These prices can increase substantially based on the level of power factor correction, level of filtering, and other application specific requirements.

The major cost components in such a system tend to be the low frequency input transformer and reactor, switchgear, and specific engineering required at site for installation, commissioning or for identifying and solving power factor and harmonic related problems. Although this technology has several disadvantages, in particular where size, input power factor and input harmonics are concerned, it is often a familiar and low cost solution. If the customer is not negatively impacted by the poor line side performance, there is little incentive for him to change, unless driven by lower equipment first cost. Thus replacement of this mature technology in the market will occur as other utility friendly solutions become cost competitive, or if the input line side performance improvement is mandated by an applicable standard.

3.2 Switched Mode Power Supplies (Hard Switching-B)

Figure 2 shows a block schematic of a switched mode power supply, again used to convert incoming ac line voltage into a controlled output dc voltage or current, and is representative of the approach used by most vendors of power supply equipment rated at 50 watts to 10 kW or so. The system typically consists of an uncontrolled diode rectifier stage to convert the incoming ac line voltage into a intermediate dc bus voltage. The dc voltage is then converted into a high frequency ac (20 to 100 kHz) waveform using a power electronic inverter. This high frequency is then coupled into a high frequency transformer which provides voltage matching and the desired isolation. The high frequency ac on the transformer secondary winding is then rectified and filtered to obtain the desired dc voltage and/or current. Control of this output voltage is effected by controlling the switching of the power inverter stage using pulse width modulation (PWM) techniques. The high frequency transformer is substantially smaller than a comparably rated 60 hertz transformer, and provides some of the best opportunity for possible cost and size reduction. Further, the output side performance of this solution is superior to the phase controlled rectifier, due to very low ripple and fast dynamic response. However, it is very difficult to realize bidirectional power flow into the ac line with this type of converter, which can be a limitation in some applications.

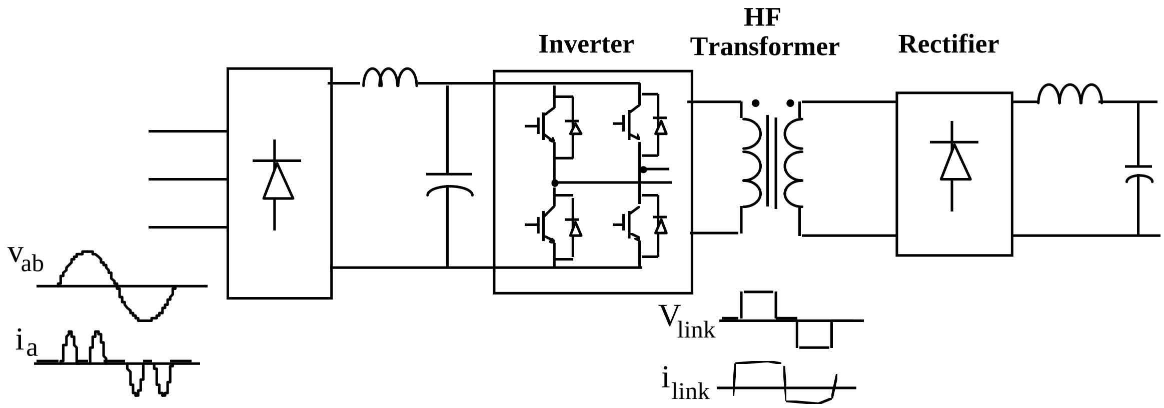

Figure 3-2
Block schematic of a hard switching switched mode power supply

On the input line side, switched mode power supplies can also have significant problems. The simplest input rectifier stage consists of a diode bridge and filter capacitor. This causes very high current distortion in the input ac line currents (130% THD), even though the fundamental power factor (displacement factor) remains close to unity. In smaller-power single-phase input systems, the trend is to add a power factor correction stage to the input rectifier, so that sinusoidal input currents and unity power factor are obtained. Such solutions are extensively used today in switched mode power supplies for computers and office equipment rated at less than 1.5 kW or so, but have not been applied as widely in higher-power commercial and industrial applications, primarily due to cost, which is higher by approximately 10%. Another class of converters integrates the power processing stage with the power factor corrections stage into a single stage to reduce the overall cost of the system. However, these solutions are limited to applications rated at less than a few hundred watts, and they tend to have poorer harmonic performance than the two stage circuits.

For three phase input ac line, an active power factor correction stage is possible, but adds excessive cost, and is rarely used. A simpler and more cost effective solution in three phase input applications involves using a dc side reactor after the diode bridge. This brings the input ac current harmonic distortion down from 130% THD without the reactor to 30-40% THD with the reactor, while maintaining unity displacement factor, for an overall power factor of 0.93-0.95. It should be noted that passive harmonic filtering solutions are not effective in this application, primarily because the filter capacitance gives substantially leading power factor for the system, often causing a voltage boost on the ac line due to interactions with the plant or local transformer. Newer solutions which are more cost effective and realize unity power factor and low input current THD levels are actively being investigated by researchers, but are not commercially available.

Another important issue on the input side relates to electro-magnetic interference (EMI) generated by the fast switching action of the power devices in the inverter stage of the power supply of the end-use equipment. This EMI can interfere with the operation of other sensitive electronic and computer equipment in the vicinity. The FCC provides limits on the levels of EMI that consumer and commercial appliances generate. The power supply is a primary source of EMI, and its containment in a cost effective manner is important to the overall power supply design. The FCC limits are not applied to industrial devices at present, as these are typically custom designed low-volume production units. However, all products sold in Europe now have to conform to European CE norms on conducted and radiated EMI. It is anticipated that the US will eventually follow with a similar requirement. Hard switching inverter based power supplies typically generate high levels of EMI, and require appropriate EMI filters to suppress conducted EMI levels to meet FCC or CE norms. These filters can be very expensive, particularly at power levels above a few kilowatts.

Cost factors associated with switched mode power supplies are well understood, as the technology is fairly mature, at least at power levels below a few kilowatts. In the high-volume computer power supply area, power supplies rated at 200 to 1500 watts are made for costs approaching $100-200 per kilowatt. These are highly standardized designs with single or multiple output voltages, no user settable points, and no monitoring or display functions. Manufacturing volumes for some of these specific designs approach 10-12 million pieces per year. In order to realize increased flexibility in the final configuration, an increasingly common approach is through the use of dc/dc converter modules. Pioneered initially by Vicor Corporation, such dc/dc converter modules are now offered by many major vendors. The final power supply is then configured using one or more of these modules along with commonly available diode rectifiers and filter capacitors. This approach is somewhat more expensive but allows much higher flexibility to the end user. The dc/dc modules are available in power ratings of up to several hundred watts, and are available in high volume in many standard ratings.

The fundamental problem with cost comes when one approaches custom designs and/or higher power levels. For custom designs which require user settable constant voltage and constant current modes of operation, display of voltage and current set points and outputs, and analog or digital I/O interface, the cost can be much higher, approaching $350 - 1000 per kilowatt. The higher engineering and component costs of these more sophisticated designs are amortized over smaller production volumes. Further, the smaller volumes also can result in higher distribution and sales costs on a per unit basis. Together, these factors result in higher cost.

Another important limitation results from the difficulty of scaling these designs to higher power levels. The power devices at lower power levels are MOSFETs, which are capable of switching at high frequencies of 50-250 kHz (and higher). However, one has to use IGBTs at higher voltages and power levels, causing a reduction in the switching frequency that can be effectively attained. Secondly, conventional high frequency power transformers are limited in their thermal handling capability by their structure to about 1-3 kilowatts, and current levels of 50-100 Amperes. Switched mode designs at higher power levels typically utilize several dc/dc converters in parallel to realize the desired ratings. For instance, in the telecommunications area, it is common to see a 48 V-100 to 200 Ampere dc power supply realized with 2 or 3 dc/dc converter stages in parallel. The power supplies are then further configured in parallel to realize systems rated at 500 to 10,000 Amperes dc. The paralleling approach within a power supply typically has higher cost and lower reliability than a single stage solution. As a consequence, this approach is rarely used for applications requiring more than 10 kW or so in a single power supply stage. In terms of cost competitiveness, it is also clear why phase controlled rectifiers still dominate at higher power levels, and why switched mode solutions have become widely accepted at lower power levels.

3.3 Switched Mode Power Supplies (Soft Switching-C)

A newer form of switching technique, referred to as soft switching, allows higher performance in switched mode power supplies. Soft switching supplies include two fundamental types of power conversion; resonant mode converters and zero voltage transition converters. The block schematic of a soft switching power supply, shown in Fig. 3, is essentially the same as for the more conventional hard switching switched mode power supply shown in Figure 2, as is a general discussion of its operation. The primary difference is the use of zero voltage switching for the power devices. This reduces device switching losses, and allows switching at higher frequencies than is conventionally possible with given devices and at a given power level. It also realizes a slower rate of change on the device voltage, resulting in lower EMI levels. These differences have significant impact on the power range that can be realized.

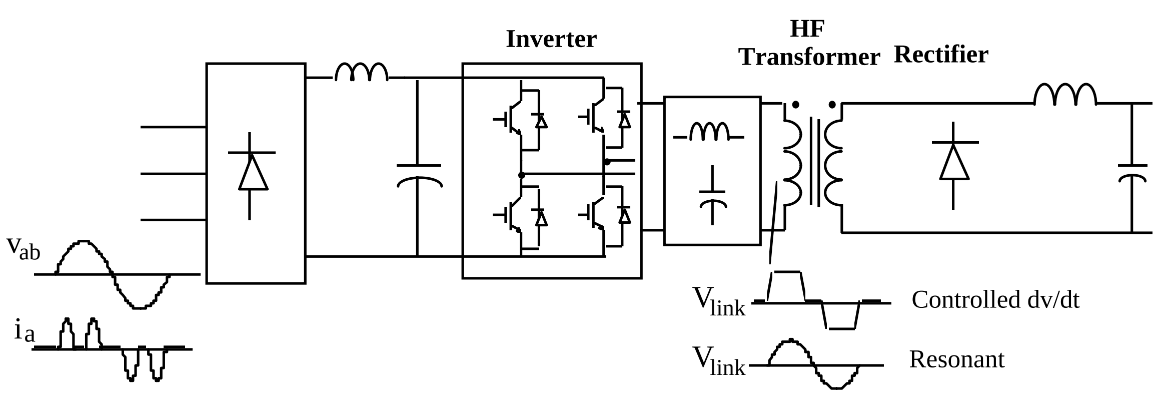

Figure 3-3
Block schematic of a soft switching switched mode power supply

The reduction in device switching losses, for instance, allow MOSFETs to switch at 150 to 1000 kHz at power levels of up to 10 kW, and IGBTs to switch at 20 to 75 kHz at up to 150 kW and possibly higher. The lower switching rate (dv/dt) on the inverter output also allows use with transformers which have high inter-winding capacitance, common in high voltage applications. This allows the use of switched mode supplies in many medical imaging applications such as X-ray tubes and Magnetic Resonance Imaging (MRI). The lower dv/dt also results in lower EMI for soft switching power supplies. Similarly, soft switching power supplies can be more easily designed to include parasitics associated with components and packaging, and generally offer better performance as performance limits are pushed on the technology.

Another recent advance which has helped in pushing the power limits on switched mode technology is the use of newer high frequency magnetic structures. Two examples of new transformer designs, seen to be a fundamental limitation in switchmode technology (see B), are matrix transformers used at lower power levels, and coaxial winding transformers used at higher power levels. Both approaches demonstrate dramatic improvements in thermal handling capability, and can realize higher power levels and power densities than hitherto possible. In particular, coaxial winding transformers have been used to realize current levels of over 1000 Amperes and power levels of more than 150 kilowatts in a single power conversion stage, without in any way reaching the limits of the technology's capabilities. These magnetic structures also offer the best performance with the higher switching frequencies that can be realized with soft switching power supplies.

In all other respects, in particular input line side performance, soft switching switched mode power supplies are similar to their hard switching counterparts. Consequently, in power ranges where competitive products are available, costs of both technologies tend to be similar. However, as one approaches the limits of conventional switched mode technology, a significant difference in cost becomes apparent. For instance, in the 10 to 150 kilowatt power range, soft switching power supplies are available in moderate volumes at $100 to $250 per kilowatt, depending on the options and the production volume. Given the substantially higher input and output side performance and smaller size of these power supplies, when compared with the phase controlled supplies (A), this price is considered to be fairly competitive. Further, given that this technology is in its infancy and does not have the level of maturity of phase controlled converters, it is likely that this technology type can realize significant further cost reduction and has the potential to substantially penetrate the phase controlled market for power levels of up to 500 kilowatts or so.

3.4 High Frequency Inverters- D

Many processes require direct ac power at frequencies other than the utility frequency of 60 hertz. If the areas of motor drives and UPS systems are excluded, a large number of ‘electro-technologies’ working from fixed frequency ac voltages require high frequencies of 10 to 500 kHz. The required power level ranges from a few hundred watts to a megawatt. The similarities to the switched mode power supplies, in particular the soft switching circuits, are strikingly high. Many, if not most, of the high frequency inverters use some form of resonant or zero voltage transition soft switching inverter as the basic building block. However, there are two basic approaches to realizing the high frequency inverter. The first uses a voltage source inverter, shown in Figure 4, and is used typically at lower power levels of 0.1 to 200 kW or so. The second approach uses a current source inverter, shown in Figure 5, and is used at higher power levels ranging from 50 to 1000 kW or so.

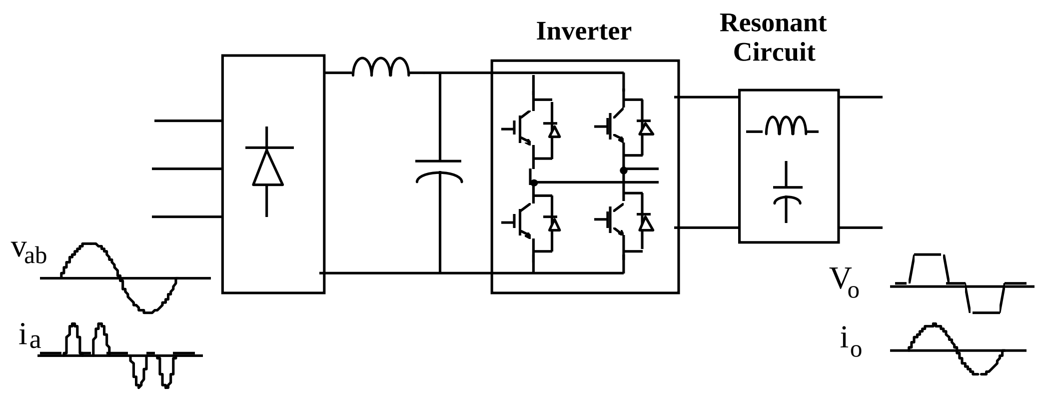

Figure 3-4
Resonant voltage source inverter

The voltage source inverter can be either of the hard switching or soft switching type. In low power applications, such as electronic lamp ballast, hard switching inverters are sometimes used. In almost all other applications, and frequently in lamp ballast as well, the inverter of choice is normally a resonant soft switching inverter, in which an inductor (L) and a capacitor (C) form a resonant tank. Operation in the resonant mode allows high frequency operation in the 20 to 500 kHz range. How the resonant voltage is utilized depends on the end use application. For instance, in lamp ballast, the voltage is used to excite one or more fluorescent lamp tubes. In induction cooking, current is induced in the cooking pan to be heated. In ozonation equipment, the voltage is used to generate a silent discharge and a sustaining voltage to maximize the production of ozone. Another important use for high frequency inverters concerns industrial processes based on induction heating, induction hardening, induction welding and other similar applications. In such applications, the inductor is typically a work coil which also functions as a transformer. The transformer couples current into the piece to be heated without making direct contact with it. Localized heating then occurs in specific parts of the work piece to accomplish the desired objective.

In higher power applications, a current source approach is often used to realize the soft switching resonant inverters. For high frequency operation, as targeted here, the power device of choice is the MOSFET. The MOSFET is used with a diode in series, as shown in Figure 5, and is fed by a current source formed by a phase controlled rectifier and large filter inductor on the input side. This technique is used to realize large converters rated at up to 1000 kW at frequencies of up to 500 kHz. Each inverter is realized using banks of MOSFETs in parallel, each of which has to share power in a reasonable manner. Device and converter packaging for high frequency parasitic effects and thermal management are key factors in these complex water-cooled designs, and few companies have wide ranging expertise in this field. Applications for this type of technology include induction heating, tube seam welding, gear hardening and levitation melting.

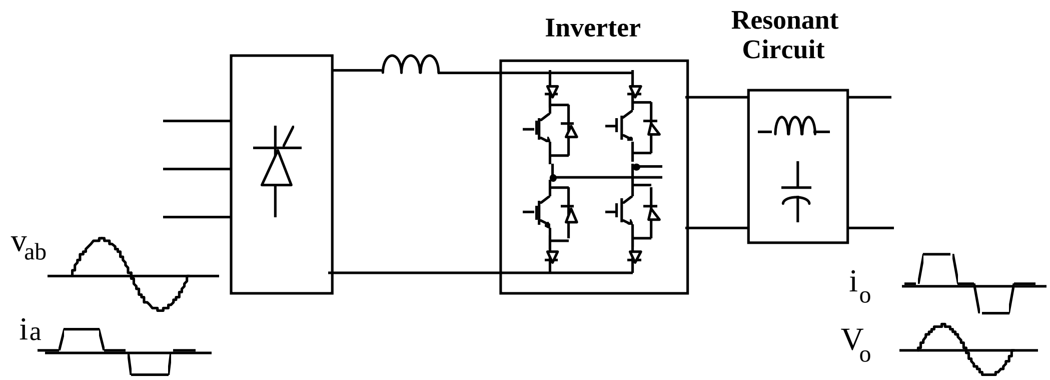

Figure 3-5
Resonant current source inverter

Voltage source designs are taking an increasing share of the market, once again because the designs tend to be simpler and less expensive. The ruggedness and shoot through protection associated with current source inverters is becoming less of an issue as devices become capable of operating under such conditions. Further, the bulk of the dc reactor and the poor power factor associated with the input phase converter in current source inverters are continuing issues. It also seems likely that IGBTs will increasingly displace MOSFETs as the device of choice in applications rated at up to 150 kHz and 500 kW, due to substantially lower cost. IGBTs will also provide the opportunity to move from complex water cooled systems to simpler air cooled systems. It should be noted that water cooling is often required for cooling the work coil, and in such cases converter performance can be substantially improved by using water cooling. High performance IGBT inverters have already been demonstrated in the dc/dc area and in research laboratories, and it seems to only be a matter of time before this transition occurs in industry.

Cost of the lower power voltage source inverters tends to be very competitive, and depends on the application. For instance, the fluorescent ballast industry is even more competitive than the computer power supply industry. Prices for single lamp ballast (integrated inside some newer lamps) is targeted at $2-5 for a 15 to 25 watt converter.

Four lamp ballast, rated at 160 watts, have a target sale price of $16-$20. Although this still seems to be in the $100 per kVA range, and does not seem outrageous, these are extremely aggressive prices which are driven consistently lower by global competition. Another application which could be subject to similar competitive forces is in the field of induction cooking for residential and commercial applications. Despite strong efforts by several global players, this market has not realized its full potential, apparently due to lack of strong customer interest. The market is somewhat better outside the US, although still substantially short of market projections. In spite of this, prices for a 1 kW domestic induction cooker is targeted at $100, including the power supply, the cooking coil, the cabinet, an attractive user interface and the cabinet. Target price for the power supply is less than $35, including the ac/dc rectifier stage and the input EMI filter, once again very aggressive.

For industrial applications, the market is very fragmented, and as specific designs incorporate years of experience integrating the power supply to the end-use processes, it is rarely that the power supply is sold as a separate piece of equipment. Consequently, it is somewhat difficult to accurately estimate prices for the power supply in specialized equipment such as induction heating or hardening. In such cases, a technical discussion of the cost factors is the best that is readily possible. In any case, it seems that as the converter structure gets simplified, the costs should reasonably align with similar converters used in switchmode dc/dc converters. A target of $200 to $400 per kilowatt seems to be achievable at some not so distant time in the future.

3.5 Low/Medium Frequency Inverters- E

Low to medium frequency inverters operate in the 1 to 20 kHz range at power levels ranging from 10 kW to 1 MW, and have typically used thyristor based current source inverters. The concept is similar to that discussed for current source inverters in section 3.4, but use thyristor devices in the inverter section, as shown in Figure 6. The use of the resonant LC tank allows turn-off of thyristors in the circuit, and to operate them at frequencies approaching 20 kHz, provided fast recovery thyristors are used. Thyristors have, at least in the past, been lower cost compared to gate turn-off devices, and have been preferred in this application.

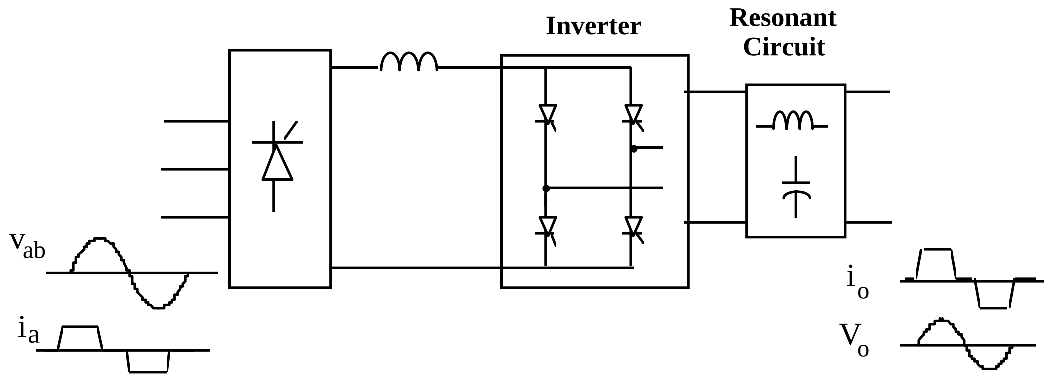

Figure 3-6
Thyristor based current source inverter

Once again, the most important end-use application for this kind of power supply is possibly in induction heating and melting. The inverter output is coupled in through the work-coil and transformer into the piece to be heated.. The frequency and power level are selected based on the type of heating, the depth of heating and the material to be heated. The circuit has to be robust enough to withstand sudden load application and removal without any operating problems. In the past, the current source inverter has been preferred due to its robustness. With the advent of newer devices such as IGBTs, and the low volume requirements for fast thyristors, it seems that the IGBT or other gate turn-off device will eventually replace the thyristor inverter in this application as well. The advantages in terms of first cost and input ac side performance have been extensively discussed in the previous sections.

Several approaches are possible for the use of voltage source inverters in low and medium frequency inverters. The conventional technique of resonant conversion can be used, where the tank is excited at a desired voltage and amplitude. The LC tank components, including the work coil, are individually tuned to a specific work piece and heating profile. The converter itself is generally self oscillating, sensing the instantaneous tank voltage and controlling the device switching so as to sustain the resonance. In current source systems, power control over a wide range is accomplished by varying the value of the dc current source via the input thyristor rectifier bridge. This is somewhat more difficult in voltage source inverters as the dc bus voltage is usually fixed. An alternate technique varies the frequency of the resonant tank so as to vary the effective amplitude of the voltage exciting the work-coil, and thus the power delivered to the work piece. This approach tends to cause high device losses and widely varying excitation frequencies in the work piece, and is not highly desirable.

In recent years, the use of resonant dc link type of inverters and pulse density modulation techniques has been proposed for power control in induction heating applications with great success. At lower frequencies it is possible to operate resonant dc link inverters at up to 200 kVA, and to obtain sinusoidal currents in the load at any arbitrary frequency up to 2 kHz, without requiring a resonant LC tank on the load side. Such approaches have been reported in Japanese literature, but may not be widely available commercially yet. It is anticipated that the use of such techniques will increase the viability of voltage source inverters, and will increase the market penetration, when compared with current source inverters. However, current source inverters will possibly continue to dominate at the highest power levels.

3.6 High Current Choppers (F)

This category of converter is used in very special applications requiring high dc current (similar approach can be used for high dc voltage applications as well) at power levels ranging from 200 kW to 4 MW. Typical applications for such supplies, in particular high current supplies, would be for metal extraction from an ore slurry, electroplating, electrowinning of metals such as copper and zinc, deposition of copper, electrochemical cells, and metal refining. Ratings for these supplies range from 40,000 Amperes at 350 volts and 150,000 Amperes at 50 volts, down to 1000 to 5000 Amperes at 50 to 600 volts.

The conventional approach to realizing these power supplies is through phase controlled rectifiers and its variants. However, the input power factor for phase controlled converters is rather poor. Further, the harmonic currents do not conform to IEEE 519 unless pulse numbers of 24 or higher are utilized. It is becoming common to have equipment specifications for high power converter based systems list compliance with harmonic current levels as specified by IEEE 519, and a unity displacement factor for the converter, as a basic requirement. Phase controlled converters require switchable harmonic filters to meet both the power factor and harmonic current requirement.

Figure 7 shows a relatively new technique which is being used to realize unity power factor in high power converter systems and in motor drives. The system uses a zig-zag winding transformer with multiple output windings to realize unity power factor and low input harmonic currents. Each output winding ac voltage is connected to a module as shown in Figure 7. The module takes in the ac voltage, rectifies it to an intermediate dc voltage, and then uses a high current dc/dc converter, referred to as a chopper, to give a controlled dc current output. Multiple modules can then be paralleled to realize high currents at modest voltages. Alternatively, the modules can be stacked in series to get high output dc voltage. Each module can be designed to provide up to 2,500 Amperes at 100 to 500 volts dc., with 10 to 30 modules per system. The system can also be designed with (N+1) units, so that full performance is retained in spite of a module failure, thus substantially increasing system reliability.

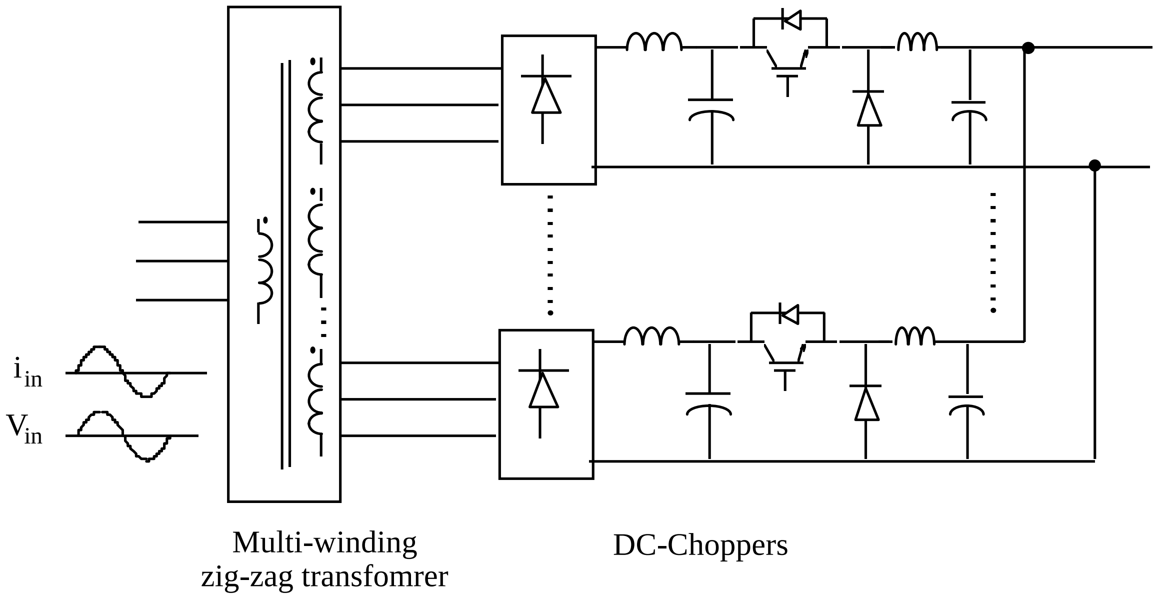

Figure 3-7
Multi-module high current choppers

This approach allows system operation with unity power factor, and allows a modular approach to realizing high power levels. The modules are based on readily available IGBT devices, and can be lower cost due to a standardized manufacturing process. The control of the output is very precise, due to the high frequency switching possible in the choppers. However, the transformer is complex and expensive, and the construction of a large number of modules and their integration into the overall system adds substantial cost. These converters are seen to be cost competitive in situations where the improved utility side performance is an integral part of the overall system specification. Fortunately for the proponents of this technology, improved input line side performance is now required on a majority of high power contracts, and its popularity is likely to continue to increase in the years ahead.

3.7 Other Approaches (G)

The above sections have discussed some of the primary techniques that are presently in use, and show signs of increasing or maintaining their share in the market. It is clear that the overall list of available technologies is substantially more expansive than presented in Table 2.1. Some of these are focused on niche markets, or represent technologies which are being replaced by newer power electronics based technologies. The list of power conversion techniques used in industrial control includes tap changing transformers, servo stabilizer variable transformers, ferroresonant transformers, and motor-generator sets for controlling 60 hertz ac power or dc power delivered to loads. Most of these techniques tend to involve bulky equipment, with relatively slow response times, and are being replaced by power electronics equipment.

For applications requiring electrical power which cannot easily be generated by rotating or passive means, solid state converters have frequently been used. For instance, in ultra precision dc supply applications, a linear regulated power supply is often used. These feature ultra low noise levels and can offer virtually ripple free precision outputs. However, the efficiency is very poor, and power range is limited to several kilowatts. On the high frequency end, particularly for induction heating, one can use vacuum tube based or solid state RF amplifiers to provide power for induction heating in the 100 kHz to 10 MHz range. Special rotating machines have also been available to handle frequencies in the low hundreds of kilohertz. Once again, power electronics solutions, when applicable seem to provide a lower-cost higher-efficiency solution than most of the techniques that are sometimes used. Power electronics solutions also tend to offer lower first cost and operating cost, especially in the long term.

3.8 Conclusions

This section has provided a brief technical description of key technologies in the dc and ac power supply area. The discussion has covered a wide range of solutions, many of them established in industry and widely available from several vendors, and several which represent new cutting edge technologies which show great promise for the future. This section has also provided a brief discussion of factors which limit continued performance improvements and cost reductions. In several 'standard' technology areas, an estimate of current equipment costs are also indicated. The next section will provide a representative listing of types of equipment, detailing the type of power supply used, technical features, vendors for such equipment, and costs where possible.

4

POWER SUPPLY APPLICATIONS

Previous chapters have examined the core technology associated with specific types of power supplies used in a variety of industrial, commercial and residential applications. It is often difficult to comprehend that the power supply retains a high level of commonality over very diverse end-use applications. Improvements in power supply technology in this electro-technology sector have been slow in occurring, partly due to the fragmentation of the industry that is providing power supplies to the end-use OEM's. Few companies, with the exception of vertically integrated multi-nationals such as Fuji Electric and ABB, have the ability to develop a new component, vis-a-vis a new power supply, for a low volume product such as induction heating. One of the primary objectives of this report is to identify such commonalities so that scarce resources can be focused on providing benefit to as broad a cross section of power supply users as possible.

This chapter provides a discussion of several examples of end-use applications for power supplies. These examples include cathodic protection, electroplating, battery formation, battery charging, ozonation systems and induction heating systems. A fact sheet is prepared for each application, which includes principles of operation, followed by ratings, vendors, type of core power supply technology used, drivers for improvements, and the technologies by which these improvements could be realized.

It is possible to detect a consistent thread in terms of the main drivers that provide the motivation to develop the next generation of equipment. The needs can be categorized by the type of core power converter technology that is targeted for use. These are developed later in this chapter, following the fact sheets, which are presented next.

Cathodic Protection

Cathodic protection is a method of controlling corrosion of buried, partially buried, and submerged metallic structures. Cathodic protection systems eliminate the anodic regions which exist on a metal by passing direct current to the metal surface. The direct current is discharged from electrodes (anodes) installed in the electrolyte adjacent to or near the structure (cathode) being protected. This will minimize corrosion if the direct current is of sufficient magnitude and is distributed properly over the entire surface to be protected.

Companies: Good All Electric, Inverpower

Applications: Cathodic protection for underground tanks, ships, oil platforms, bridges and merged metallic structures

Input Power: AC

Output Power: DC

Typical Ratings:

Table 4-1
Cathodic Protection, Typical Ratings

Input Power	Output Voltage	Output Current	Cooling	Technology
Single phase	80-100 VDC	4-120ADC	None	Tapped Transf.,G
Three Phase	12-120VDC	6-450ADC	None	Tapped Transf.,G
Single Phase	8-100VDC	4-160ADC	Air/Oil	Phase Controlled,A
Three Phase	8-120VDC	6-450ADC	Air/Oil	Phase Controlled,A
120VAC/240VAC	24VDC	12ADC	Air	Phase Controlled,A
120VAC/240VAC	18VDC/ 100VDC	25-100A DC/ 5-20ADC	Air	Switchmode,B

Potential For Improvement

Drivers:

Smaller size, lower cost and improved power factor are important drivers. Corrosion protection frequently involves long periods over which operation of the unit has to be guaranteed. Opportunity for moving towards 'smart supplies' which can be polled, or which report on status periodically, or upon a fault, to a central data gathering and reporting center via a modem. Finally unattended operation will move the industry towards 'self-tuning' systems, which can set the optimum terminal voltage and current through sensing the electrode and load parameters on a dynamic and continuous basis.

Possible Technologies

Moving towards 'smart supplies' will shift the industry towards switched-mode type of supplies (B and C). The benefits of smaller size and higher power factor will automatically follow. Cost of switched mode supplies is already competitive with phase controlled systems at up to 100 kW.

Induction Cooking

Figure 4-1
Example of Induction Cooking

Induction Cooking Systems use electromagnetic energy to induce currents in the cooking utensil itself, thus heating it. An induction cooktop cooks without a flame or radiant heat source and eliminates the liability and danger of gas jets and red hot electric burners. An induction cooking system costs about 6-8¢ per hour versus butane which could run as much as $1.75 an hour.

Companies: CookTek Systems, Luxine

Applications: Induction cooktops for commercial and home use

Input Power: AC

Output Power: HF AC

Typical Ratings:

Table 4-2
Induction Cooking, Typical Ratings

Input Power	Output Power	Temperature	Cooling	Technology
Single phase 120VAC	300W-1500W	122° - 410°F	Air	Switchmode: hard switching, D
Single Phase 240VAC	3-5kW	122° - 410°F	Air	Switchmode: hard switching, D

Potential for Improvements

Drivers:

Cost competitiveness is a major barrier in the US market, particularly in residential applications. Volume production is an important factor in meeting cost targets. Revenues accruing from a life time of electrical energy use (as against gas) need to be used to provide a first cost reduction for the end-use customer.

Possible Technologies

Improvements in low cost soft switching converter topologies, and fabrication techniques for integrating low cost cooking coils with the electronics are key to meeting desired cost objectives.

Induction Heating / Hardening

Figure 4-2
Induction Heating / Hardening

Induction heating utilizes electromagnetic induction to induce eddy currents in a work piece. The Joule heat generated by the eddy current loss is used for heating, melting and hardening. Efficient and speedy heating can be achieved by concentrating energy to the object where heat is required. The volume of the energy input can be changed by varying the intensity of the magnetic field so as to the adjust the heating speed. The depth to which heating occurs in the work-piece can be controlled via the frequency of excitation. This represents a widely used technology in which power conversion technology advances have improved process efficacy and productivity substantially.

Companies: Lepel,, Inductoheat, Fuji Electric,

Applications: Melting, forging, roll forming, extrusion, surface hardening, quenching, tempering, annealing, welding, brazing, soldering, drying, liquid heating

Input Power: AC

Output Power: Medium to high frequency AC

Typical Ratings:

Table 4-3
Induction Heating / Hardening, Typical Ratings

Input Power	Out. Voltage	Output Power	Cooling	Technology
Single Phase 120VAC/240VAC	200-800Vrms 10 kHz-1 MHz	500W	Air	D, G and E
Three Phase 240/380/460VAC	200-800Vrms 1 kHz - 500 kHz	5-25kW	Air	D,E and G
Three Phase 240V/460VAC	150V / 2000Vrms 400 Hz - 500 kHz	20-2000kW	Air/Water	D, E

Potential for Improvements

Drivers:

The higher power induction heating inverters tend to be very bulky due to the dc reactor required to realize the current source. Further, the use of thyristors on the input converter results in poor and variable input power factor. Finally, the need to use many small MOSFET's to realize the desired output power levels, results in very complex electro-mechanical-thermal designs which are expensive.

Possible Technologies

The advent of soft switching IGBT's in voltage source circuits offers the potential of greatly simplifying the power converter structure, and thus cost. The use of new approaches for power control such as pulse density modulation open up the possibility of further cost reductions. The voltage source inverter input stage can be designed for higher input power factor as well.

High-Concentration Ozone Generators

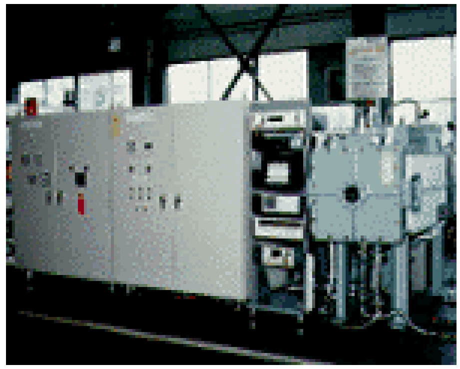

Figure 4-3
High-Concentration Ozone Generators

Ozone is a gas produced in nature by ultra violet rays from the sun or by lightning bolts during a thunderstorm. Ozone has proven itself as an effective combatant against microbiological contaminants such as bacteria, virus, protozoa, algae, etc. and is known as an excellent air and water purifying agent worldwide. When ozone is applied as a gas for water treatment in the spa, hot tubs or pools, it effectively destroys bacteria and virus more rapidly than any other disinfectant chemical such as chlorine or bromine. The water stays sparkling clean and fresh smelling. Ozone production is done by high frequency and UV excitation of oxygen.

Companies: Fuji Electric, Ozonia,, Astex, Del Industries

Applications: Water purification, air purification, disinfection of hospital waste, clothes washing, paper and pulp bleaching, chemical oxidation, etc.

Input Power: AC

Output Power: HF AC

Typical Ratings: Sizes vary from small ozone generators for residential use which operate from a simple ultra-violet lamp, to industrial grade equipment which produces ozone for a purifying a large city's water supply.

Potential for Improvements:

Drivers:

Ozone generation is typically a very inefficient process, with conversion efficiency's in the 2-3% range. Significant opportunity exists for improving plant efficacy by optimizing the geometry and excitation of the ozone generation tubes.

Possible Technologies

Use of advanced modulation techniques has been shown to have some impact on the ozone generation efficiency. Improved understanding of the physics of ozone generation need to be the basis for design of a matched tube and converter.

Plating/Anodizing/Electrowinning Applications

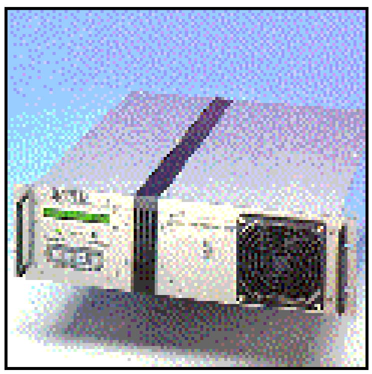

Figure 4-4
Plating/Anodizing/Electrowinning Applications

Electroplating is a electrochemical process for depositing a thin layer of metal on, in most cases, a metallic base. Items are electroplated to prevent corrosion, to obtain a hard surface or an attractive surface, to purify metals, or to separate metals for quantitative analysis. Cadmium, chromium, copper, gold, nickel, silver, and tin are the metals most often used in plating. In the process of electroplating, the object to be coated is placed in a solution (called a bath) and is connected to the negative terminal of a dc supply. Another conductor, often composed of the coating metal, is connected to the positive terminal of the electric source. A steady direct current of low voltage, usually from 1 to 6 V, is required for the process. When the current is passed through the solution, atoms of the plating metal deposit out of the solution onto the cathode, the negative electrode. These atoms are replaced in the bath by atoms from the anode (positive electrode), if it is composed of the same metal, as with copper and silver. Otherwise they are replaced by periodic additions of salt to the bath, as with gold and chromium.

Companies: Rapid Power Technologies, Kraft, Electronic Measurements Inc. (EMI), Soft Switching Technologies, Dynatronix, ABB, Inverpower, Robicon

Applications: Electroplating, electrolytic coloring, pulse anodizing, hard coat anodizing, sulfuric and chromic acid anodizing, electrowinning (Cu, Al, Ag, ..), electrochemical strip lines

Input Power: AC

Output Power: High Current Low Voltage DC

Typical Ratings:

Table 4-4
Plating/Anodizing/Electowinning Applications, Typical Ratings

Input Power	Out. Voltage/ Current	Output Power	Cooling	Technology
Single Phase 120VAC/240VAC	6-48V to 500 A DC	100W – 5kW	Air	A, B, C and G
Three Phase 240 VAC/460 VAC	6V-100V to 10,000 A DC	5-100kW	Air/Water	A, B, C and G
Three Phase 460-4400 VAC	Up to 1000V, to 120,000 A DC	200 kW - 10 MW	Air/Water	A, F

Potential for Improvements

Drivers:

The environment in electroplating shops tends to be hot, humid and highly corrosive. As a result, power supplies are either located in a separate room with air exchange to the outside, or use water cooling. In cases where conventionally air-cooled supplies are located in close proximity to the tanks, corrosion limits equipment life to as little as a few months. Further, as currents can reach thousands of amperes and hundreds of kilowatts, phase controlled converters dominate the application area. This results in poor power factor and bulky size due to a low frequency transformer. Switchmode power supplies have made some inroads into this market over the last five year. It has also been recently reported that accurate control of high frequency ripple current in the output can be used to control the plating finish. This offers yet another value added function that the power supply can provide in the plating process. . In electrowinning applications, the higher power rating (1-10 MW) of the converter, causes harmonic problems for other utility customers. Low input harmonic levels are thus highly desirable, and are often being specified via IEEE 519 recommended standard.

Possible Technologies

The use of switchmode power supplies can offer higher input power factor, smaller size, and better ripple control than phase controlled rectifiers. In volume, it also seems that the cost of the two solutions can be competitive. An important development, which has recently become available commercially, is that of completely sealed air-cooled switchmode plating supplies. These supplies can be located near the plating tanks, and are not subject to corrosion. Thermal management in such systems is a challenge, and presently limits the ratings that are available. Higher power applications, such as electrowinning will move towards high input power factor solutions such as massively paralleled high current choppers fed from zig-zag winding transformers. Such solutions have been demonstrated to be cost competitive with phase controlled solutions, and offer power factors of 0.98 or better.

Battery Chargers for Consumer Equipment

Figure 4-5
Battery Changer

Battery charging is one of the fastest growing fields areas due to the advent of batteries in portable electronics equipment. The approach used in charging batteries has a dramatic impact on battery life. Smart chargers which compensate for memory effects, which allow fast charging, and which maximize battery life are important for customers increasingly dependent on battery operated appliances. Battery powered equipment is being applied in widely varying applications ranging from portable computers, video cameras, cellular phones, electric bikes, lawnmowers and vacuum cleaners.

Companies: Advanced Charger Technology, Intronics, Norvik, Exide

Applications: Battery chargers for portable electronics equipment, and for consumer mobile equipment (not including electric vehicles)

Input Power: AC

Output Power: DC, 1.2 to 60 volts, 0.1 to 25 amperes

Typical Ratings:

Table 4-5
Battery Chargers for Consumer Equipment, Typical Ratings

Input Power	Out. Voltage/ Current	Output Power	Cooling	Technology
Single Phase 120VAC/240 VAC	1.2-12 volts, up to 10A	Up to 1kW	Air	Switchmode B
1 or 3 Phase 240 VAC	6 - 60 volts, up to 25A	Up to 1.5kW	Air	Switchmode B, Phase Controlled A

Potential for Improvements

Drivers:

Major driver is the ability of the charger to fast charge the battery and to get maximum life out of the battery. Further, a state of charge indicator on batteries would be highly desirable from a customers view point. A single charger that can handle any type of battery, recognizing its characteristics and adapting itself accordingly is highly desirable. Integration of the charger into the battery is the final step.

Possible Technologies

Several vendors claim benefits through modified charging algorithms. These include interrupted charging, pulse charging, monitoring of battery environmental parameters, etc., all in an effort to tailor the charge being sent into the battery. Coupling new charging algorithms with new topologies for basic or pulse charging, and new techniques for charge equalization offer the most potential benefit.

Plasma Spraying

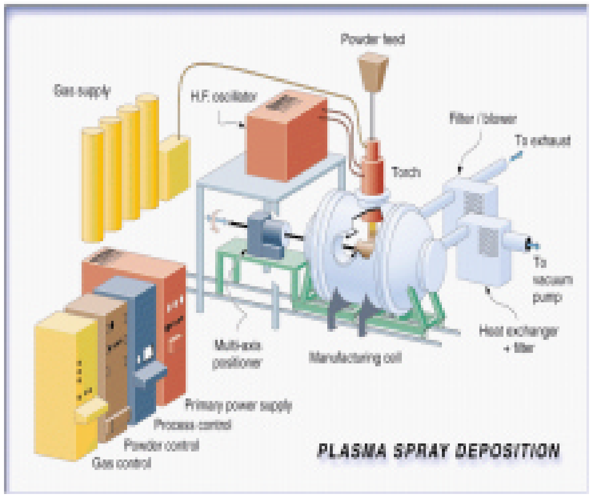

Figure 4-6
Plasma Spray Deposition

Spray deposition of surface coatings has been finding a wide range of industrial applications covering automobiles, steel and ship-building industry, as well as aerospace and biological applications because of its unique capability to form thick coatings of various materials such as metals, ceramics, cermets and composites. To meet such intensifying requirements for the quality of sprayed coatings, various spraying technologies have been emerging such as LPPS (low pressure plasma spray), HVOF (high velocity oxy-fuel) spray, RF plasma spray and so on.

The essence of the coating formation process is the collision of a sprayed powder particle onto a solid surface.. When an incident particle is a molten metal or ceramic particle with diameter in the range of 10 to 100 microns with a velocity of 100 m/s, it results is a very fast and complicated phenomenon involving heat and momentum transfer, wetting, disintegration of liquid sheets and threads, rapid solidification, and elasto-plastic deformation.

Companies: Dynapower, Sulzer Metco, Miller Thermal

Applications: LPPS (low pressure plasma spray), HVOF (high velocity oxy-fuel) spray, RF plasma spray

Input Power: AC, 230/460 volts

Output Power: DC 10 to 100 kW, 100 volts DC, 1000 ADC, also requires a superimposed high frequency source to initiate an arc to start the plasma, 2000 Ampere pulses.

Converter Type: Phase controlled converter (A)

Potential for Improvements:

Drivers:

Process requirements in plasma spraying are calling for faster control to dynamically control variations in the coating. This dynamic requirement cannot be fulfilled by existing phase controlled technology. Further, efficiency, power factor and power supply size are becoming increasingly important issues.

Possible Technologies

Conventional technology based on phase controlled converters will be replaced by switchmode (B,C) units which feature improved utility specifications and higher efficiency, as well as offer improved dynamic response. Cost targets set by the existing phase controlled rectifier technology seem to be achievable.

Battery Formation/Testing

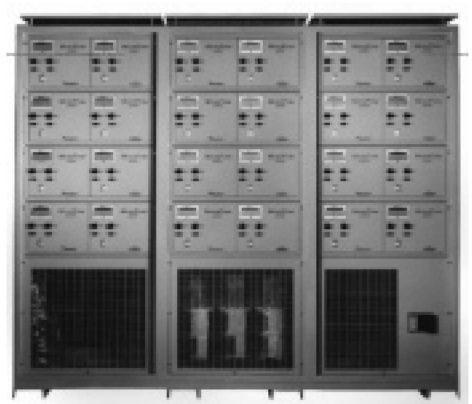

Figure 4-7
Battery Formation/Testing

Battery formation is the process by which the electrolyte in lead acid batteries are 'formed' during the manufacturing process via cycles of controlled charging and discharging. Batteries are normally formed in long strings with 100-250 batteries in series. This is a cost sensitive application, particularly for the high volume batteries targeted at automotive applications. With more sophisticated batteries targeting energy storage, better optimization of the charging process is required. This may require pulse charging and discharging, regenerative power flow, and control of charge and discharge currents over a wide current range.

Companies: Firing Circuits, Digitron

Applications: Formation of lead acid battery, battery life testing

Input Power: AC, 230/460 VAC

Output Power: DC, 200 to 350 volts DC, 25 Amperes per string, system power 100 to 250 kW

Typical Ratings:

Table 4-6
Battery Formation/Testing Typical Ratings

Input Power	Out. Voltage/ Current	Output Power	Cooling	Technology
Three Phase 240 VAC	360V, up to 50A	Up to 12kW	Air	Switchmode, Phase Controlled (A,B)
Three Phase 380/460 VAC	360V, up to 50A	Up to 50kW	Air	Switchmode, Phase controlled(A,B)

Potential for Improvements:

Drivers:

Battery formation for new battery types promises to require more sophisticated forming algorithms to extract optimal life, energy and power density from the battery. Formation and testing equipment will need to become smart along with the chargers.

Possible Technologies

Once again, move towards switchmode technology (B,C) seems to be dictated. New solutions may be required to handle the regenerative requirements for some of the battery formation and testing.

Industrial Fork Lift Trucks

Figure 4-8
Industrial Forklift Trucks

Industrial lift trucks, or forklifts, are widely used in a variety of industries. The forklifts are gas or battery powered. Battery powered forklifts are required for operation in enclosed spaces, but could also be used in outdoor applications. In the US, electric lift trucks make up only 40% of the lift truck market. This compares with a 70% market share in Europe. At present, battery management for lift trucks requires up to three sets of rapid change batteries. An alternate approach, based on rapid charging of the batteries, would allow operation with a single set of batteries, saving significantly on first cost and space required.

Companies: Norvik, GNB, Exide, Aerovironment, Soft Switching Technologies

Applications: Rapid charging of off road vehicles, on board rapid chargers, can also be applied in other industrial applications involving battery energy storage

Input Power: AC, 230/460 volts AC

Output Power: DC, normal charging 48 volts DC, up to 200 Amperes, fast charging, up to 600 Amperes

Typical Ratings:

Table 4-7
Industrial Fork Lift Trucks, Typical Ratings

Input Power	Out. Voltage/ Current	Output Power	Cooling	Technology
Three Phase 240 VAC, 460VAC	40-100V, 600A	Up to 30kW	Air	Switchmode, Phase controlled (A,B,C)

Potential for Improvements:

Drivers:

For normal charging, the main drivers are cost and size. Reducing both will cause a corresponding reduction in plant space needed. For fast chargers, cost and demonstrated ability to maintain battery life and charge acceptance are critical factors. A final objective would be to integrate the battery module and charger/battery management system into one unit.

Possible Technologies

Size reduction will be driven by a move towards switched mode technologies (B,C). Cost of fast chargers is still an issue, although recent indications suggest that substantial price reduction is possible compared with similarly rated units that are presently available.

Automotive Applications

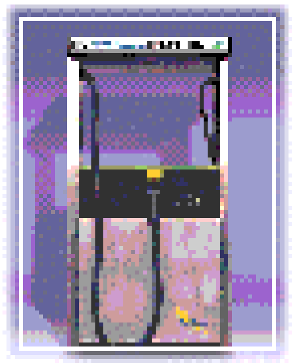

Figure 4-9
Automotive Applications

Fast charging is expected to jump-start the building of electric-vehicle infrastructure and will significantly advance the usable range of electric vehicles by charging a battery pack in a matter of minutes instead of hours. Charging infrastructure is an EV technology enabler and will appreciably enhance the utilization of electric vehicles for both private and fleet applications. Charger cost and the availability of public charging are critical factors in a consumer's decision to purchase an electric vehicle. It is anticipated that electric utilities will be one of the first major users of electric vehicle fleets, and will benefit significantly from the availability of fast chargers.

Companies: Delco, Norvik, Aerovironment,

Applications: EV battery charging, also applies to off-road EV’s

Input Power: AC, 230 VAC 1 or 3 phase up to 20 kW, 460 volts for >25 kW

Output Power: DC, typically 200-350 volts

Typical Ratings:

Table 4-8
Automotive Applications, Typical Ratings

Input Power	Out. Voltage/ Current	Output Power	Cooling	Technology
Three Phase 240 VAC, 460VAC	200-400V	1kW-150kW	Air	Phase controlled, Switchmode (A,B,C)

Potential for Improvements:

Drivers:

Electric vehicle chargers represent a fundamental infrastructure issue. Improved customer acceptance of EV's, particularly in fleet situations will drive the solution towards some form of fast charging. Size, cost and utility side performance are major issues. Control of current over a wide range, particularly at low levels, will allow proper algorithms for battery float and end of charging.

Possible Technologies

Phase controlled rectifiers (A) dominate the area of chargers today. However, the emergence of inductive chargers gives reason to believe that switchmode and high frequency inverter solutions (B,C,D) will eventually dominate. Size, utility performance and operation under light currents are major reasons.

Recommendations for Research

This technology assessment report has sought to examine some of the dominant electro-technology end-use applications, and to identify the underlying common power conversion technology. The focus has been on those low volume applications, where individual markets typically cannot cost-effectively support significant development in the power supply technology, so as to realize the accruing benefits due to higher efficiency, higher productivity, smaller size and lower cost. Further, the fragmentation of the power supply industry into small players, and the diversity in the customer base, makes internal growth of technology difficult. The utilities, as being a common supply of electrical energy to all identified applications, can play a role in improving the current status of power supply technology, as used in the electro-technology sector.

Several trends are seen to emerge as dominant for future applications. These include small size, fast dynamic response, high efficiency, customized price/performance trade-offs, good input ac line power quality, and finally lower first and lower operating cost. Low power commercial and residential power supply applications, such as for personal computers and for microwave ovens, have seen an order of magnitude reduction in cost while simultaneously realizing smaller size and better performance. Similar technology and volume drivers exist in the targeted area as well.

For instance, many of the phase controlled rectifiers presently used in the 1 to 200 kilowatt range could be replaced by switched mode power supplies. The high frequency inversion function always operates from the input line voltage, giving some level of standardization on the power converter across a wide range of applications. The high frequency transformer provides matching between load and supply voltage. Very few manufacturers of switched mode supplies have the capability of realizing cost-effective converters above a few kilowatts, a factor which has limited the spread of this technology across diverse applications. Demonstration projects could begin the process of verifying the applicability of the new technology in the newer applications.

In the case of applications based on high frequency inverters for ac outputs, cost reduction is the primary objective in high-volume consumer applications. In lower-volume but higher-power industrial applications, moving towards IGBT based voltage source inverter solutions would reduce cost and size, and improve the power factor on the input side. The use of pulse density modulation as a means of controlling power to the work-piece in induction heating applications needs to be verified, as it would reduce cost substantially.

Finally, in the area of very high power dc systems such as electrowinning, the realization of a modular dc power supply to realize 10,000 to 100,000 Amperes of current output at 100 volts dc, could be based on choppers and zig-zag winding transformers, or on paralleled high-frequency isolated switched mode power supplies coupled with an active filter. Even for large electrostatic precipitators rated at 100,000 volts dc at 1-5 Amperes, a cascaded series connection of switched mode power supplies could realize a cost effective system.