Circuit Reinvention In Power Electronics And Identification Of Prior Work

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Abstract - A review of literature and patent records for industrial controls and power electronics over the past 100 years shows a pattern of circuit invention, loss and reinvention, often repeated. This has resulted in a great waste of time and effort, as well as interminable legal wrangling and the loss of useful ideas for long periods of time. This paper gives an overview of the problem using several examples of circuits of current interest. The paper then goes on to discuss searching for prior work.

I. Introduction

Industrial controls and power electronics have been part of electrical engineering since late in the 19th century. To a surprising extent the applications and performance goals first recognized by our great-grandfathers are still very much the concern of engineers today. DC-DC conversion, DC-AC inversion, AC-DC rectification, motor and process controls, illumination and a host of other applications were recognized very early and remain in the forefront of modern work. Many of the components we use to implement our designs have changed over time but the basic problems and applications have changed surprisingly little. While we have the advantage of greatly improved components and tools such as the computer, there is no evidence that we are any more intelligent or inventive than those who went before us.

In fact our greatest advantage is the legacy of the work which has been done by our predecessors. Unfortunately we often do not recognize this and much earlier work has been lost or ignored.

A review of literature and patent records reveals that the same concepts and circuits have repeatedly been invented, forgotten and re-invented. Because of the continuity in problems types, the same solutions are constantly being recreated. This represents a monumental waste of time, effort and money. Why repeat analyses and experimental work which has already been done and is often readily available in the literature? The interminable and very expensive wrangling over patent priorities is particularly unproductive. All too often these disputes are resolved by demonstrating the work in question had already been done many years in the past. It would have been much more effective to perform an adequate prior art search at the time of the patent application. Like every other sector of our society, design engineers are being forced to improve productivity and produce better solutions in less time. We simply cannot afford to waste the work of our peers and those who have gone before us.

II. Historical Examples

This section provides several examples of circuits of present active interest which have been re-invented over the years.

The Hertzian oscillator

In 1888 Heinrich Hertz demonstrated that the electromagnetic waves predicted by James Clerk Maxwell really did exist. For his experiments he used a circuit arrangement very much like that shown in figure 1[1]. This circuit was widely used in early radio transmitting equipment and was known as a Hertzian oscillator. An examination of the circuit shows that it is a continuous conduction mode flyback converter, using bi-level, hysteretic, peak current mode control with a capacitive turn-off snubber for the switches. These are all very "modern" circuit ideas. Peak current sensing to turn-off the switch is certainly a current "hot topic". The use of a capacitive snubber on the switch shows how early the need for an alternative current commutation path, to protect the switch when interrupting an inductive load, was recognized. Today a capacitor is still used for exactly this purpose even though we use very different switches. The basic physics have not changed!

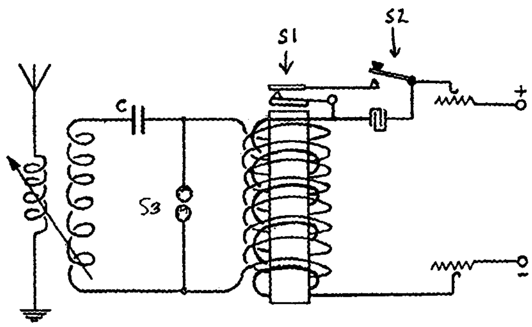


Figure 1, Hertzian oscillator

Resonant transition switching

Zero voltage switching using resonant transitions is presently a very active topic. This interest is relatively recent and it is widely thought that it represents something new. Resonant transition switching is in fact an idea with a long history. Beginning in the 1920's mobile radio equipment was widely used in automobiles, police and emergency vehicles, aircraft and by the military. Most of those platforms could provide only a low voltage (6-24V) DC power source. One of the most common means to provide the high voltages (150-800V) needed for vacuum tubes used in this equipment, was a mechanical vibrator driving a transformer. An example of such a power supply is given in figure 2. This figure is taken from a 1947 Mallory Handbook[2] but represents a technology which matured in the 1920's. The vibrator was a mechanical oscillator which chopped the input low voltage DC, producing a quasi-squarewave AC voltage across the primary of the transformer. This circuit is the direct predecessor to the transistor squarewave inverters which were created in the 1950's soon after the transistor was invented. Much of the technology of the vibrator power converters was incorporated directly into the new transistor inverters.

Note in figure 2 that there is a capacitor (referred to as the timing capacitor) which could be placed either across the primary or the secondary windings. This capacitor, along with leakage and magnetizing inductances, provided resonant transition switching

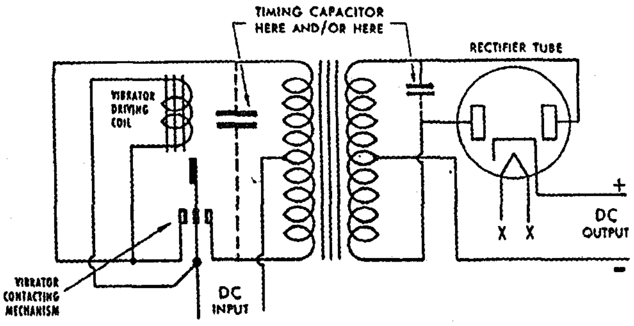


Figure 2, Vibrator converter

which greatly extended the life of the vibrator contacts. The fact that this example exactly reproduces the modern resonant transition switching can be seen in figures 3a-c which are circuit waveforms. Figure 3a shows the quasi-squarewave nature of the waveform. The deadtime (t_2 and t_4) was deliberately introduced to allow for resonant transition switching which is clearly shown in figures 3b and c. The discussion in the handbook goes on to point out the effects of too small and too large a deadtime. The concept of resonant transition switching was clearly understood by the designers of vibrator power converters.

When useful transistors became available, the vibrators were replaced with transistors with anti-parallel diodes as shown in figure 4 along with switch voltage and current waveforms. Note that the switch current was deliberately made negative at switch turn-on, with the current flowing through the anti-parallel diode, to provide zero voltage turn-on. A capacitor is used along with the transformer inductance to provide resonant transition switching. These figures are take from a 1958 Electronics article[3] which specifically addresses the issue of increasing switching efficiency by using what we now refer to as "soft switching".

Vibrator and transistor inverters were not the only applications for soft switching. Beginning the 1930's, thyratron and ignitron inverters and phase controlled rectifiers were in common use and also required switching commutation aids. When thyristors became available in the late 1950's, the earlier technology for thyratrons, ignitrons and magnetic amplifiers was adapted for the new devices. Over a period of 50 years almost every conceivable commutation circuit was examined. Commutation, using an auxiliary switch, of which much has recently been written in regard to single ended circuits such as forward and flyback converters, is a very old trick which was well explored in an amazing variety of circuits more than fifty years ago.

Zero voltage or resonant transition switching is a very good example of an old idea which has been resurrected repeatedly because even though switching device technology changes, the basic circuit function remains the same.

Boost converters and switching amplifiers

As shown earlier, the flyback converter dates back over 100 years. The buck and boost converters have also been used for a very long time. Figure 5 is taken from a patent[4] filed in 1923. Note the triode switch (9), the power source (12), the series inductor (13), the rectifier diode (14) and filter capacitor (14). These elements form a boost converter. The object of this circuit was to provide efficient amplitude modulation for an RF amplifier. The boost function was required due to the need for the peak

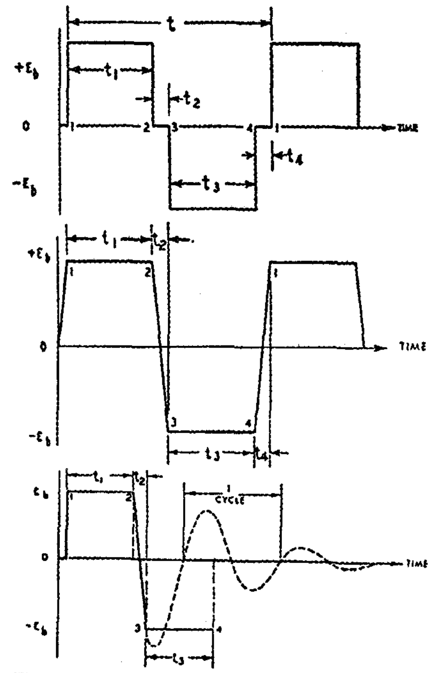


Figure 3, Resonant transition waveforms

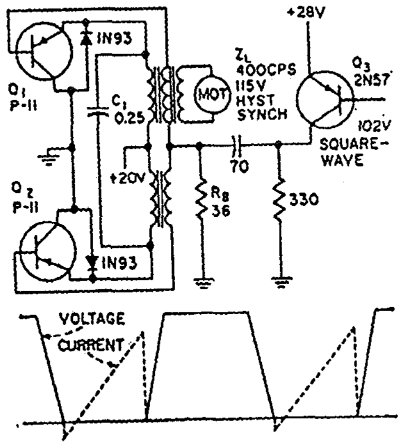


Figure 4, Soft switching inverter

modulation voltage to be approximately twice the supply voltage for the RF amplifier. Some of the circuit waveforms from the patent are also shown in figure 5. Note that a carrier, with a frequency above audio, was employed to produce pulse width modulation to drive the boost switch. The circuit is a PWM switching amplifier using a boost converter. It is fully equivalent to it's modern counterparts and was used for much the same reasons.

The two inductor rectifier

Rectifier circuits are a subject which has received a great deal of attention over a very long period of time. It is therefore surprising when something new turns up. In 1991 two papers[5,6] were presented on a "new" rectifier circuit. These papers represent a very good example of a circuit in use over a period of 50 years which dropped from sight and then reappeared. A schematic is given in figure 6.

The circuit was not however, new. It was used beginning in the early part of this century for mercury arc rectifiers and appears in early papers and texts. Figure 7a is taken from a 1919 work[7] and

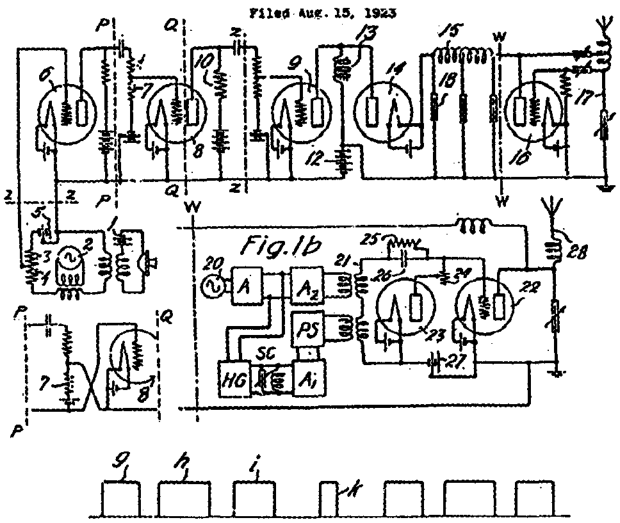


Figure 5, 1923 boost switching amplifier

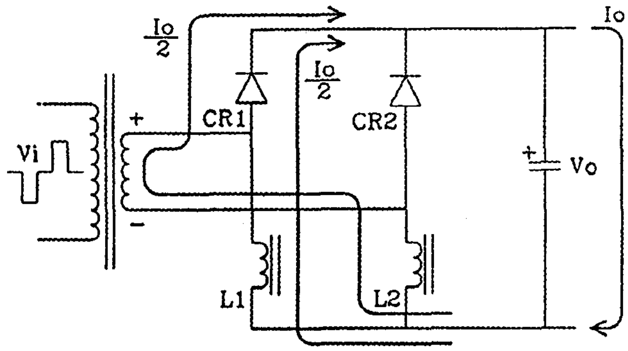
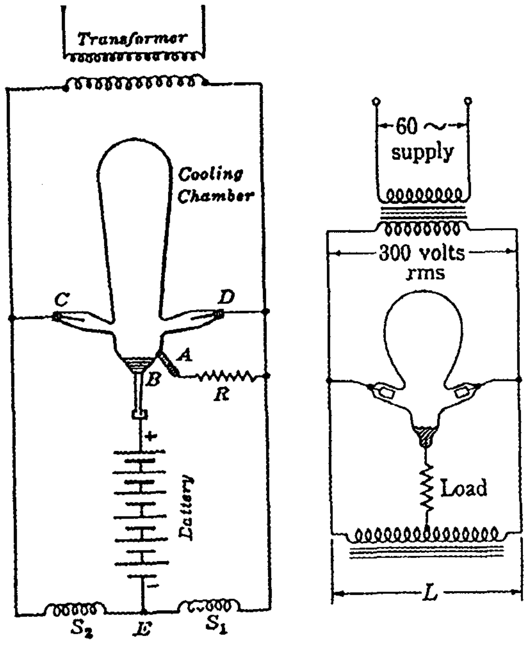


Figure 6, Two inductor rectifier



(a) (b)

Figure 7, Past two inductor rectifiers

figure 7b from a 1954 text[8]. The circuit was in continuous use during this entire period but disappeared from the literature in the late 1950's. It took over 30 years before it reappeared. Since this is a circuit which would have found useful application during this hiatus this represents a loss to designers. The version rediscovered uses two separate inductors but that is not the only version. Figure 7b shows a version which uses a tapped inductor. A careful reading of the text associated with this figure shows that the inductor was a coupled inductor with carefully controlled leakage reactance associated with each winding. In this case the older work was ahead of the more modern re-incarnation.

This circuit also provides an opportunity to show how older work can be combined with more recent circuit techniques to yield new insights into rectifier circuits. An examination of the operation of the two inductor rectifier shows that the output voltage is half the winding voltage and the DC current is twice. The circuit is a current doubler and a voltage divider. This is just the opposite of the well known voltage doubler. In the voltage doubler, the DC current is half the winding current and so it is a current divider. It can be shown that these two rectifier circuits are duals. This raises an interesting question, since the two inductor rectifier is the dual of a voltage doubler and we know of other doubler circuits, as well as higher order multipliers, are there entire families of current multiplier circuits which have not yet been explored. The answer is of course yes. For example, figure 8 shows a common voltage doubler variation. By applying duality, the current doubler appears which is an alternative to the earlier version. The procedure of applying duality to voltage multiplier circuits can be extended to triplers, quadruplers and higher order multipliers to produce current multipliers of the same order.

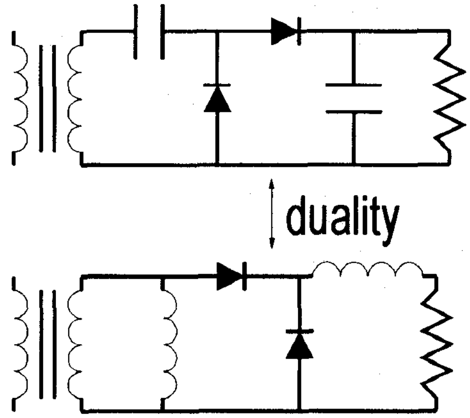


Figure 8, rectifier duals

In addition to producing new and possibly useful rectifier circuits, new switch connections can be derived by applying bilateral transformation[9,10] or time reversal duality[11] to the rectifier circuits.

This circuit has provided not only a good example of technology invented, lost and rediscovered but the advantages of revisiting old technology in the light of modern knowledge and circuit techniques. New possibilities arise from the synthesis of the two.

Intermediate capacitor energy storage

A recurring problem in power conversion is the need to transfer energy from one inductance to another. This may be because of the nature of the sources and loads or to control the ripple current introduced into either the source or load. From a efficiency point of view this represents a problem because direct transfer of energy between two inductors or two capacitors can be efficient only if the

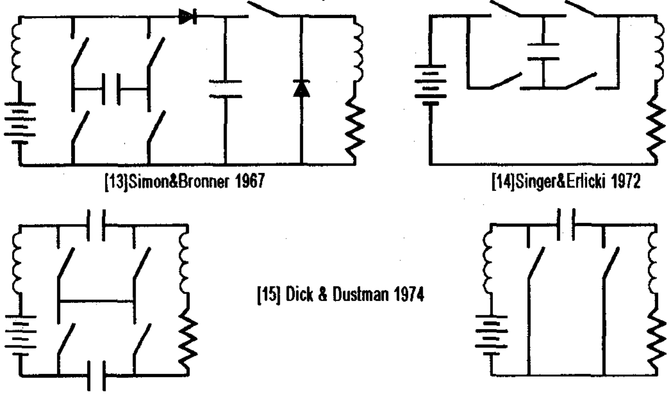


Figure 9, Intermediate capacitive energy storage

energy transferred is small compared to the energy stored in the reactive elements. In other words small ripple is required. On the other hand, large ripple can be tolerated when transferring energy from an inductor to a capacitor or vice versa, while maintaining low losses. This problem and the solution of using an intermediate energy storage capacitor have long been recognized. The intermediate capacitor may operate in either high or low ripple modes although the high ripple mode may result in a smaller capacitor. The class of circuits which use a capacitor to dynamically transfer energy from an inductive source to an inductive load are called "flying capacitor" circuits. Many variations have been invented, forgotten and reinvented over the past 70 years. A few of the more modem examples are given in figure 9 along with the date, name of the authors and a publication reference.

III. Searching For Prior Work

We could continue indefinitely giving examples of reinvention but the forgoing examples are sufficient to illustrate the problem. More important is what can we do about this? Both individuals and our professional organizations, such as the IEEE Power Electronics Society, the Industry Applications Society, the Industrial Electronics Society and others, can do a great deal to improve the situation.

Organizational approaches

Two problems face an individual beginning a search for prior work. First, the work or documents which contain the desired information must be identified and second, copies of the desired work must obtained for study. A number of commercial technical search services do exist and are frequently used, but there are some drawbacks to these:

1. Many are accessible only through colleges or universities or large companies. This is primarily due to cost.
2. Most, if not all, search programs work on key words. If you have the right key words you are very likely to get useful references but if you don't choose just the right words you may get nothing or you may have to sort through a torrent of undesired information.
3. The words we use to describe circuits and concepts tend to change somewhat over time as the technology changes. Key words which may be appropriate today may not fit work 15 or 20 years back. For example, one of the important changes over the years has been the types and names of devices used as switches. Initially the mechanical switch, like that shown in figure 1 or in rotary versions or as vibrators (figure2), was the only choice but by the turn of the century mercury arc rectifiers had appeared. In the early part of the century vacuum tubes were invented, beginning with the diode and the three element triode and followed by multi-element devices such as tetrodes and pentodes. The idea of controlling the current flow by inserting a grid in a diode was quickly applied to the mercury arc rectifiers and to other ionized gas devices such as the hydrogen thyratron. Switches included both hot and cold cathode devices. These devices allowed the creation of controlled rectifier circuits and static DC-AC inverters. Such circuits are still very popular using thyristor switches in place of the gas devices. Another variation on the mercury arc rectifier was the Ignitron. In this device conduction was initiated by striking an arc in a pool of mercury which released a cloud of mercury ions which initiated current conduction. Like a thyristor, turn-off required either a reversal of the line voltage or some active commutation circuitry. Magnetic amplifiers and saturable reactors were also used for controlled rectifiers. All of these names are needed for key word searches for early work.
4. In some cases the words used to describe circuits may be different between regions. For example, in the US the buck converter is a very well known circuit by that name. However, in England, and Europe in general, it would be called a chopper circuit. A search of IEE papers for the buck converter might not give many hits when in fact there are a multitude of chopper papers. There are many other semantic differences which can inhibit a successful search.
5. Present data bases are far from complete and frequently do not go back far enough in time.
6. On-line data bases are more readily available but in general do not provide the range of references needed.
7. Overall, most of these data bases are too broad and not complete enough to really solve the search problem in the power electronics field.

One answer to these problems is to create a specialized data base. This has been attempted by an individual, Jerrold Foutz[16], with considerable success. However, the task is well beyond a single individual and certainly would not provide compensation in proportion the great effort required. Providing such a data base with reasonable cost and accessibility, is a task more suited to an organization like the Power Electronics Society, in cooperation with other societies. Much of the work of these societies is done by volunteers and this is the kind of task which could be divided up among a large number of people, directed by the society, so the load on any individual would be reasonable. The task would also benefit from the varied experience and perspective that a large group would have. The data base could then be supplied on-line and/or via CD-ROM disk at modest cost to members of the cooperating societies. This might provide the auxiliary benefit of increasing society membership.

At present the IEEE does provide an IEEE/IEE electronic library on CD-ROM this resource contains full page copies of all IEEE and IEE publications from 1988 on. This is a wonderful resource but unfortunately the initial cost is roughly $100,000, with substantial yearly update fees. This is well out of reach for most engineers and small companies. This resource may well be available at large university libraries which will be of assistance to those able to access these locations. The major drawback, besides cost, to this library is that it only goes back to 1988, at least at present. Recent papers are usually not too difficult to obtain, it is the older work which presents the greatest problems. It is perhaps not recognized that some older material, such as the proceedings of the AIEE which go back to the 19th century, is still of current interest and potentially useful.

Hopefully, in time, the electronic library will be accessible on-line at reasonable cost. A first step has been taken. The IEEE technical advisory board has approved the placement of citation and abstract information on the IEEE web page. This will include titles, authors, abstracts and other related information on all papers from IEEE periodicals and conference proceedings. This is scheduled for early 1997. A program dubbed "JOLLY" (Journals On-Line Launch Year) has been initiated by a group of societies (Circuits and Systems, Electron Devices, Lasers and Electro-optics and Neural Networks and Signal Processing) on an experimental basis which will provide their new publications on-line for members. No doubt other societies will join in. While this will be very helpful for future papers, it does not address the search for earlier material.

The Internet is clearly the future for information retrieval. For example, some service providers are making the search facilities of Dialog available during evenings and weekends at reduced rates. This trend will continue and expand. At this time the services provided on-line are changing very rapidly and it is not clear what will be available and when. But it is clear that in the long run this will be the primary resource for searching prior work. In the mean time we will have to use more conventional methods.

Conventional Search Sources

The literature relating to power electronics is very extensive. Searching through it can be a daunting and time consuming task. Knowing where to look is a great help and the following discussion addresses many of the more common sources. One of the prime requirements is access to a good library such as that found in a large company or at a University with an engineering school. Such libraries not only have much of the material you may be looking for but will also have search resources and the ability to obtain documents from other institutions. Without such a resource searching can be very frustrating. Another important resource is the "starving graduate student". This is not a joke! An great deal of a graduate students time is spent in literature searches and it is considered an integral part of their education. Given that graduate students are rarely, if ever, paid at the going rate for working design engineers, it might very well be faster and less expensive to turn over the search to a graduate student. That would benefit both you and the student. This could be particularly effective if you do not have reasonable access to a good library.

A number of institutions have power electronics graduate programs which could be a source of a competent searcher as well as Ph.D. thesis's and internal reports on power electronics. The following list of institutions and leading professors is a starting point:

- CalTech - R. Middlebrook
- MIT- J. Kassakian
- Univ. of Arizona - A. Witulski
- Duke Univ. - T. Wilson (retired)
- Virginia Polytechnic - F. Lee
- Univ. Missouri-Columbia - R. Hoft (retired)
- Oregon State - R. Spee
- Portland State -R. Tymerski
- Univ. WA - P. Lauritzen
- Univ. Of IL, Chicago - C. Lee
- Univ. of CO - R. Ericson
- Univ. of FL - K. Ngo
- Univ. of WI - D. Divan
- Rensselaer PolyTech - D. Torry
- NC State - Art Kelly
- Auburn Univ. - M. Nelms
- Univ. SC - J. Hudgens
- Univ. MI - N. Mohan
- TX A&M - M. Eshani

Information can be grouped into the following categories:

- Citations and references in publications
- Peer reviewed journals and transactions
- Trade magazines
- Serial corporate publications
- Patent files
- Textbooks
- Government reports
- University Ph.D. thesis's

The references and citations given in technical papers are frequently the starting point for a literature search and are very important. One of the most important things we can do as individuals is to supply as complete a set of references as possible when we publish a paper. This not only gives credit where it is due but also provides the paper trail for those who wish to follow up and expand on our work. Go back as far in time as you can.

Peer review publications represent a major area for searching. For power electronics the following publications are of particular interest:

1. American Institute of Electrical Engineers (AIEE)
2. Institute of Radio Engineers (IRE)
3. Institute of Electrical Engineers (IEE - England)
4. IEEE journals, transactions and conference proceedings. In particular the following societies:
    - Aerospace and Electronic Systems
    - Consumer Electronics
    - Dielectrics and Electrical Insulation
    - Electron Devices
    - Industrial Electronics
    - Industry Applications
    - Magnetics
    - Power Electronics
    - Solid State Circuits Council

The following conference proceedings are particularly relevant:

- Applied Power Electronics Conference (APEC)
- Power Electronics Specialists Conference (PESC)

- IAS annual conference
- Intersociety Energy Conversion Engineering Conference (IECEC)
- Industrial Electronics Conference (IECON)
- International Telecommunications Energy Conference (INTELEC)

It should be kept in mind that some of the society and conference names have changed over the years and may be different going back in time. PESC for example was originally Power Conditioning Specialists Conference (1970-71) and Power Processing And Electronics Specialists Conference (1972).

There are many Conferences and Journals relating to particle accelerators, pulse modulators and high power physics work which contain interesting power electronics information. For example, much of the early work on voltage multipliers was done by physicists and appears in physics journals.

There have also been a number of power electronics conferences not under IEEE auspices. Some of these are:

- High Frequency Power Conversion conference (HFPC) [17]
- Power Conversion and Intelligent Motion (PCIM)[17]
- POWERCON[18]
- Power Sources Symposium[19]

One of the failings of peer review publications, from a design engineers point of view, is the high technical level which they strive to maintain. While this is commendable for some work, it means that many simple but very useful ideas never make it to these publications. This void has traditionally been filled by trade publications such as Electronics magazine and many others. In recent years these publications have tended not to have many articles concerning power electronics, although there are a few exceptions[20,21]. In the past however this was not so. Electronics magazine goes back into the 1930's, and is a source from many early articles on converters and inverters before the art matured to the point where they start to appear in peer reviewed publications. For example, in the 1950's when transistors became practical for low power inverters and converters, Electronics had articles on elementary circuits and in particular showed how to use transistors to replace vibrators. The transition from vibrators to transistors is well documented in Electronics and other magazines. Collections of articles from Electronics were made available[22] and can still be found in used book stores. Even hobby magazines like QST and Popular Electronics had useful information. For day to day design work these older magazines are not to be looked down on. On a number of occasions I have found prior art in old trade journals which cast doubt on present day patents.

Many large, old line companies, like RCA, ATT Bell Laboratories, Hewlett-Packard and Philips have technical journals. Some of these go back to the early part of the century and are a very valuable source of information.

The US government patent files contain a wealth of ideas both great and small. There are patent search services available, one of which is part of the Dialog search service. These are generally used by patent attorneys and corporate patent offices. While they can be very useful they tend to be relatively expensive and often miss important patents because the key words are not correct, the title is misleading, they are misclassified, the abstract reviewer does not recognize something that is relevant or they do not go back far enough in time.

A number of years ago the US patent office created and began selling a program on CD-ROM called CASSIS (Classification And Search Support Information System). This program, which is updated regularly by subscription, contains data base search software and a listing of all US patents beginning in 1969. The data includes patent numbers, patent titles and a short abstract describing the patent. This material is available at moderate cost from the patent office. The major failing of this software is that it only goes back to 1969 and the entries are very brief. For all that it is still very useful.

Much of the information in CASSIS is now becoming available on-line from the patent office web site (uspto.gov). A recent visit to the site gave access to material very much like that contained in CASSIS except that it began later (1976). It is not yet possible to access the complete text and drawings of patents from this source but hopefully that capability will evolve in time.

If it is necessary to go back further in time or to obtain a better description of the patent, including a diagram, the patent gazettes are available in most large public libraries. The gazettes, along with the classification information, represent the most widely available patent search medium which goes back the furthest in time. Searching through them can be tedious because a typical year will fill one to four feet of shelf space.

Some major city libraries and state libraries are repositories for government documents and patent information. They will have complete copies of patents on reels of microfilm and a suitable reader. With the reader it is possible to see the entire patent, text and figures. Some libraries will also have readers which allow the patents to be printed out directly to take with you.

There are services, including the patent office and the library repositories, which will provide full copies of patents. The patent office charges are very modest but take some time since they are sent by mail. Private services can provide much faster service (fax for example) but are substantially more expensive.

A very import source of early information is older books in the field. The term "power electronics" is relatively recent. In the early part of the century the subject was referred to as "industrial electricity" and later on as "industrial electronics" or "industrial controls". Many texts with titles incorporating these names were written and are still available in technical libraries and used technical book stores[23].

In last 30 years a significant number of Ph.D. students with dissertations are on subjects in power electronics have been graduated. A large number of Ph.D. thesis exist which are a rich source of both direct information and references to earlier work. These are often free for the asking or provided at very nominal charge. If you know some of these graduates working in the field, ask them for a copy of their thesis or where to obtain one. In addition graduate programs often have internal reports on subjects of interest. The earlier list of institutions should serve as a starting point for locating for these thesis's and reports.

Another source of out of print books and thesis's on microfilm or hard copy is University Microfilm International[24]. They have a very wide variety of material.

Foreign Sources

The sources discussed in the previous section focused primarily on U.S. publications in English. There are many other sources for power electronics work world wide. In particular the Europeans have been very active in power electronics since the beginning of the century. In fact during the 20's and 30's the British and German work in inverters, converters and magnetic amplifiers was well in advance of U.S. work. More recently the Russians have done a great deal of work in power electronics. The main barriers to accessing this work are language and source availability.

There is a great deal of power electronics activity in India and most of that work is published in English. The problem is that most of the Indian journals and publications are not available outside of India. There are however, many engineers from India working in the U.S. who may be able to assist in locating this work. The Japanese also have a very active power electronics program and publish a great deal of material. Most, but not all, of this material is in Japanese and therefore not readily accessible for the average design engineer. Japanese power electronics patents are particularly prolific. In recent years the Japanese have tended to apply for a U.S. patent in addition to the Japanese patent so that much of that work can be traced via U.S. patents.

For the multi-lingual researcher, there is a rich storehouse of information in non-English publications, particularly in German, Russian and Japanese.

IV. Summary

The goal of this paper has been to identify a problem which afflicts our discipline, to illustrate its pervasiveness with some examples and to make suggestions on what to do about it. In the restricted space available an exhaustive exposition is not possible but it is hoped that sufficient material has been presented to stimulate the reader to acknowledge the problem and we, as individuals and a group, can start to find remedies. The problem will never be totally overcome but there is a lot we can do, especially in this age of computer access to information.

V. Acknowledgment

I would like to express my appreciation to Nathan Sokal for the switching amplifier example. Nat Sokal and Ed Bloom also provided many other examples which did not make it into this paper because of space limits. Jerrold Foutz provided great help on data bases and Internet resources. Dong Tan and Bob White read the draft manuscript and made a number of helpful suggestions.

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