The Evolution of Power Electronics

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***Abstract*—Distinctive attributes of power electronics equipment are high power capability, controllability and static switching to meet the goals of high efficiency and high dependability. Aspects of the early history of power electronics are traced from magnetic amplifiers, thyratrons, and ignitrons to power semiconductors.**

***Index Terms*—AC–AC power conversion, AC–DC power conversion, DC–AC power conversion, DC–DC power conversion, history, magnetic amplifiers, power conversion, power electronics.**

I. Introduction

POWER electronics has a history that is much older than many of us practicing in the field today are likely to realize. As we will see, its growth and development have not been what one would call smooth and orderly. The "life changing" episodes that have brought about the most dramatic changes in the field have been largely unanticipated.

To provide a framework both for looking backward toward our roots and at the same time for better understanding the context in which power electronics engineers work today, it is helpful to adopt the following working definition:

Power electronics is the technology associated with the efficient conversion, control and conditioning of electric power by static means from its available input form into the desired electrical output form.

This technology encompasses the effective use of electrical and electronic components, the application of linear and nonlinear circuit and control theory, the employment of skillful design techniques, and the development of sophisticated analytical tools toward achieving the following purpose:

The goal of power electronics is to control the flow of energy from an electrical source to an electrical load with high efficiency, high availability, high reliability, small size, light weight, and low cost.

We begin by identifying certain significant technical features that set power electronic systems apart from other electrical systems. In addition, we point out features that serve to identify four classes of power electronic systems. Within this context, we then look back into the history of electrical engineering and seek to identify a few of the people and events that have been particularly influential in shaping some of the major developments in the ever changing field of power electronics.

As we have often heard, "Beauty is in the eye of the beholder." One could also say, "History is in the eye of the historian." For this reason, it needs to be clearly understood from the outset that the author is neither a historian nor even what might be described as a serious student of history. The author is one who considers himself a serious engineer, who has had more than forty years of experience in government, private industry and teaching, concentrating most of his professional effort in the area we usually identify today as power electronics. As such, he has had the good fortune to observe at close range many of the events and to know personally many of the individuals who have had and will yet have a major hand in shaping the direction of this field during the last half of the 20th century and into the 21st century.

In preparing the material for this paper, the author has tried to be as careful in recounting events of the past as he would in describing a laboratory experiment. The reader, however, should be alert to the fact that it is upon the memory of individuals rather than hard documentation that some of the described events rest.

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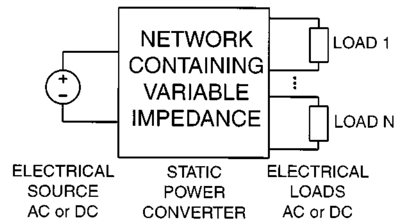

Fig. 1. To control the flow of electric energy between a source and one or more loads requires an intervening variable impedance.

II. Distinguishing Features of Power Electronics

A. General Requirements

In this section, we first identify certain features that are characteristic of power electronic systems in general, and then other features that serve to distinguish one class or type of power electronics system from another [1]. Of the many synonymous titles applied to power electronics equipment such as electronic power processor, static power converter, power conditioner, and so forth, the almost universal inclusion of the word *power* connotes the important fact that a primary goal of this equipment is the ability to process substantial amounts of electric power, ideally, as much as desired by any application load.

Fig. 1 illustrates one of the basic functions performed by all power electronic systems. The power electronics equipment controls the flow of electric energy between a source of alternating or direct current and one or more electrical loads that require alternating or direct current. The flow of power is *controlled* and regulated to meet the requirements of the load(s) by varying the electrical impedance of one or more elements internal to the power converter that is situated between the source and the load(s).

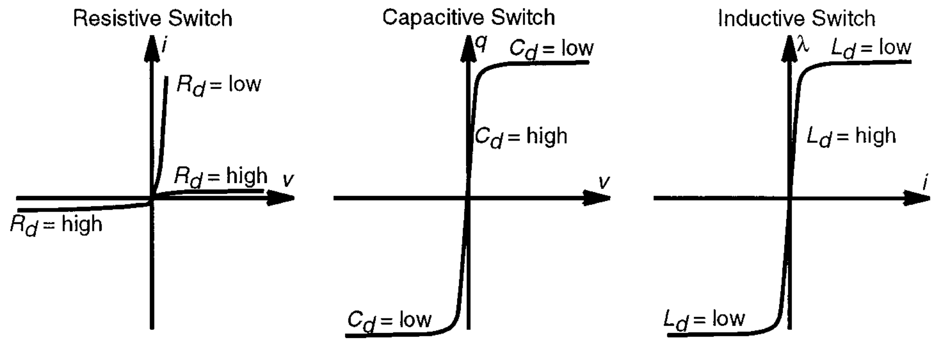

Fig. 2. To be as efficient as possible, power converters require that the differential impedance—resistive, capacitive, or inductive—change as quickly as possible between its two extreme values.

The earlier stated goal of high reliability implies that the use of parts with known short unpredictable life-time limitations such as tubes employing heaters and filaments or certain types of electrolytic capacitors should be avoided. The goal of high availability suggests that moving parts that require periodic maintenance or replacement are also undesirable. This is particularly true when these components are in the principal power-flow path and involved in the regular establishment and interruption of current as an essential part of the power conversion process. This is the reason for the important word *static* appearing in our definition of power electronics.

Most power electronics circuits can be modeled adequately by an electrical network composed of controlled sources and lumped purely resistive, capacitive, and inductive elements in which the current entering one terminal of any two-terminal element appears instantaneously at the other terminal. In order for a static power converter as shown in Fig. 1 to be as efficient as possible, the variable impedance—be it resistive, capacitive, or inductive—in the main power path between the source and load should change as rapidly as possible between as high a value and as low a value as possible. In other words, it is desirable that the impedance switch between values that are orders of magnitude apart. The sketch in the first column of Fig. 2 shows a resistive switch such as a transistor which, in response to a signal at a third terminal, can change its first-quadrant value of differential resistance R_d back and forth between a high and low value. Column two shows the charge-versus-voltage characteristic of a two-terminal capacitive element whose differential capacitance C_d can appear to switch between a high and low value by changing quickly between regions of operation. The sketch in column three shows the flux-linkage-versus-current characteristic of a typical saturable reactor which can act as an inductive–impedance switch that can change between a high value of differential inductance L_d when the magnetic path is unsaturated and a low value of L_d when it is saturated.

B. Distinctive Features Among Types of Power Converters

Power electronic equipment can be divided into four broad classifications.

AC power input and ac power output.
AC power input and dc power output.
DC power input and ac power output.
DC power input and dc power output.

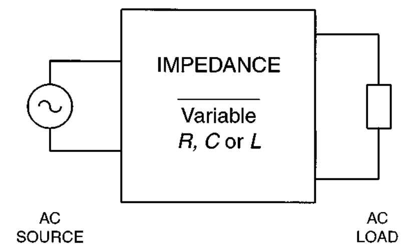

Fig. 3. AC power flow can be controlled and regulated by a change in resistive, capacitive, or inductive impedance within the converter.

We examine next some of the conditions that distinguish one class from another.

Within the first class of power converters that provide ac-to-ac power processing, the variable impedance that switches value can be either resistive, capacitive, or inductive as indicated in Fig. 3. In its simplest manifestation, the high-impedance value is inserted in the main power-flow path between the source and the load for a time interval that can be identified as t_{high} and then is replaced by the low-impedance value for a time interval t_{low}. The cycle is then repeated. The frequency and waveform at the ac load are thus directly dependent on those of the ac source. This is the type of converter most often thought of when referring to an ac power controller.

Ac-to-ac conversion is also possible where the frequency and waveforms of the input and the output are independent of each other, but this is fundamentally a combination of the basic processes in class-two and class-three power conditioners. In some cases, such converters are said to have a dc link.

For converters in the second class, ac power flow can be changed to dc only by a resistive impedance element with a nonlinear characteristic that is asymmetrical such as indicated in Fig. 4. This conversion process is usually referred to as rectification. To be included within the scope of power electronics, however, the rectification process must include the attribute of controllability.

Before discussing the third class of power conditioners illustrated in Fig. 5 that converts dc to ac, we consider in more detail the nature of the ac load in Figs. 1 and 3. In most situations, the load can be thought of as a network of impedances with the frequency and waveform at the load terminals established principally by the source and activities taking place within the converter. However, some ac loads contain within themselves an ac

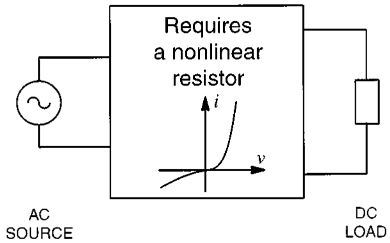

Fig. 4. AC power can be changed into dc power only through a nonlinear asymmetrical resistance, e.g., a rectifier.

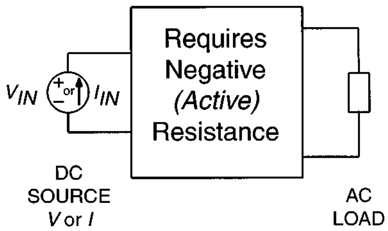

Fig. 5. DC power can be changed into ac power only through action of an active resistive element, i.e., one containing a region of negative slope.

source that is sufficiently stiff so as to establish the frequency and waveform of the output voltage or current. Under these circumstances, it is the rate of flow of energy between the source and the load that is controlled by the power conditioner. In the early days, when the source was a dc energy source and the load was a stiff ac energy source this type of power conditioning was often called "inverted rectification."

If we assume that the only source of energy in Fig. 5 is the dc source, then certain requirements must be met. In order to convert energy from the dc source into ac voltages and currents for the load, one or more special nonlinear devices, called active resistors that possess a region of negative slope such as illustrated in Fig. 6, are required. Moreover, the negative resistance must be positioned so as to form a closed series path that contains the dc power source but no capacitors. An active resistor is one whose value can be made to vary between at least two dc operating points (V_1, I_1) and (V_2, I_2) such that when the voltage $V_2 > V_1$, the current $I_2 < I_1$. The maximum dc to ac power inversion capability of an active resistor that spends equal time at each of its two dc operating points is

$$P_{\mathrm{ac(max)}} = (V_2 - V_1)(I_1 - I_2)/4. \tag{1}$$

This power is equal to one-fourth of the area enclosed in the dashed rectangles of Fig. 6.

The fourth class of power converters is the dc-to-dc converter illustrated in Fig. 7. Using the symbols in the figure, we undertake to define carefully this type of converter.

> *A dc-to-dc converter is any network that can have as its sole source of energy a constant dc voltage V_{IN} or a constant dc current I_{IN} and can provide dc output power such that $V_{\mathrm{OUT}} > V_{\mathrm{IN}}$ or $I_{\mathrm{OUT}} > I_{\mathrm{IN}}$.*

This definition says that a dc-to-dc converter must be capable of providing at its output terminals an average voltage that is higher than the average voltage at the input terminals, or it must be capable of providing an average output current that is higher than the average input current. This definition excludes such circuits as series or shunt regulators, which accomplish a change in dc voltage or current level between input and output simply by dissipating power.

It can further be shown that any dc-to-dc conversion process requires that a certain minimum amount of ac power must be generated within the dc-to-dc converter as an intermediate step. If $I_{\mathrm{OUT}} > I_{\mathrm{IN}}$, the minimum ac power that must be generated is

$$P_{\mathrm{ac(min)}} = V_{\mathrm{OUT}}(I_{\mathrm{OUT}} - I_{\mathrm{IN}}). \tag{2}$$

If $V_{\mathrm{OUT}} > V_{\mathrm{IN}}$, then

$$P_{\mathrm{ac(min)}} = I_{\mathrm{OUT}}(V_{\mathrm{OUT}} - V_{\mathrm{IN}}). \tag{3}$$

There is, however, no upper limit, and 100% of the dc input power to the converter may be converted to ac power as an intermediate step in the dc-to-dc conversion process.

III. A Brief History of Power Electronics

Having identified and considered some of the basic attributes of electronic power converters in general and pointed to some of the fundamental features that distinguish one type of power converter from another, we now look back briefly into the history of electrical engineering to identify some of the major events that have shaped the growth of power electronics into the major industry that it is today.

In the last two decades there have been several excellent articles that review the historical development of power electronics from different points of view. As might be expected, the greatest amount of literature emphasizes adjustable speed drives for rotating machines. The 1982 article by Owen *et al.* [2], expanded upon two years later by Owen [3], recounts in an interesting fashion the early days of motor drives along with photographs of early equipment and excerpts from the work of early pioneers. A comprehensive collection of the dates of the major milestones in power electronics is given along with similar dates for purpose of comparison with the major events in rotating electric machinery and automatic control theory. A somewhat broader summary of early developments is given in the twelve-page introduction to the comprehensive, almost eleven-hundred-entry bibliography compiled by Van Wyk [4]. The 1990 article by Heumann does an effective job of providing updated information on the field of motor drives [5]. In all of the above articles, the impact of the evolution in the capabilities of the devices used to establish and to interrupt the flow of current from mechanical devices, to vacuum and gas-filled tubes, to semiconductors are discussed. The articles by Pelly [6], Hoft [7], Nishihara [8], and Ohno [9] focus their attention on the changes brought about since the development of semiconductors. Two recent articles that look both backward and forward in time are by Severns [10] and by Bose [11]; while chapter one of the introductory textbook by Krein provides an interesting motivational history from the 1880's to many of today's applications [12].

My choice for the beginning date of power electronics, as defined in Section I, is the year 1912. This is the year that E. F. W. Alexanderson of the General Electric Company applied for a patent on a method for modulating the current from a high-frequency alternator so that it could be used for radio telephony

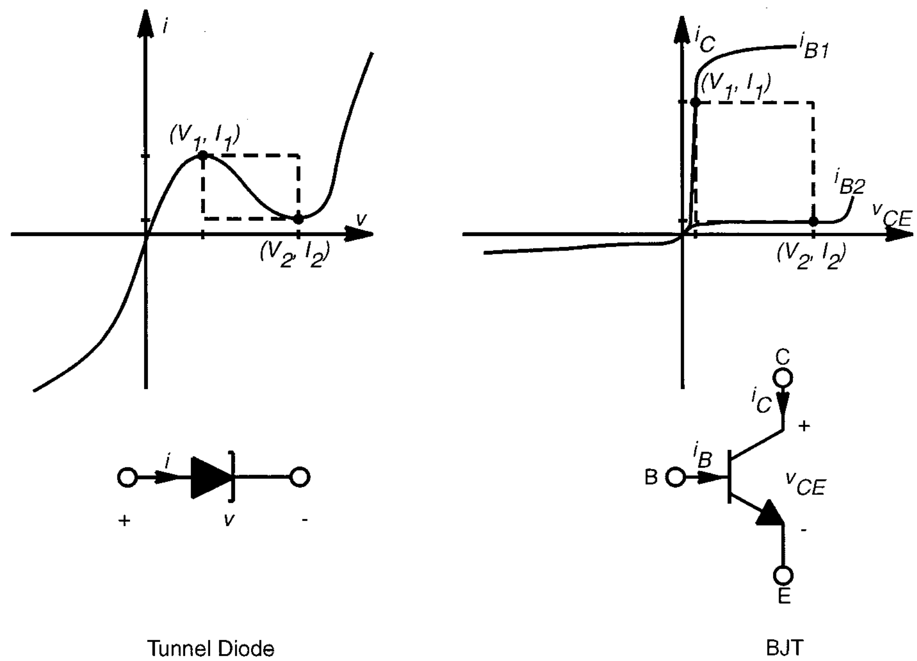

Fig. 6. Two examples of active resistance.

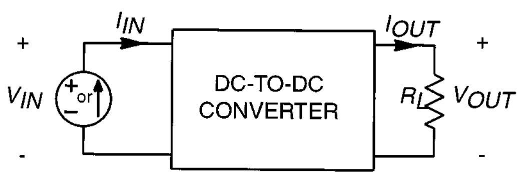

Fig. 7. For dc-to-dc conversion, either the output voltage must be higher than the input voltage or the output current must be higher than the input current.

[3], [13]. At first, this may seem to be a very strange choice for the first application of power electronics, but not because the name Alexanderson is unfamiliar. His many contributions during more than a 30-year period are certainly among the most prominent [2], but the year 1912 and the topic radio telephony may be unfamiliar. The device that Alexanderson patented was the first to meet all the requirements of our earlier-stated definition for power electronics, and it did a very good job of meeting most of the goals we enumerated for power electronic equipment.

The circuit that Alexanderson patented was a magnetic amplifier. Two examples of early forms of magnetic amplifiers that he used are shown in Fig. 8. These circuits are also referred to in the literature as saturable reactors and transductors. The circuit on the top is a series magnetic amplifier [14] and the one on the bottom is a parallel magnetic amplifier. In both cases, the source of energy is a high-frequency ac generator $v_{\rm ac}$ and the load, shown in the diagrams as resistor R_L, is a broadcast antenna. Each magnetic core with its windings has a characteristic similar to the right-hand sketch in Fig. 2 and is called a saturable reactor. The cores are identical with each having two windings, a load or output winding of N_L turns and a control winding of N_C turns. The flow of ac power from the source, represented by the ac current i_L, is controlled by a much smaller value of direct

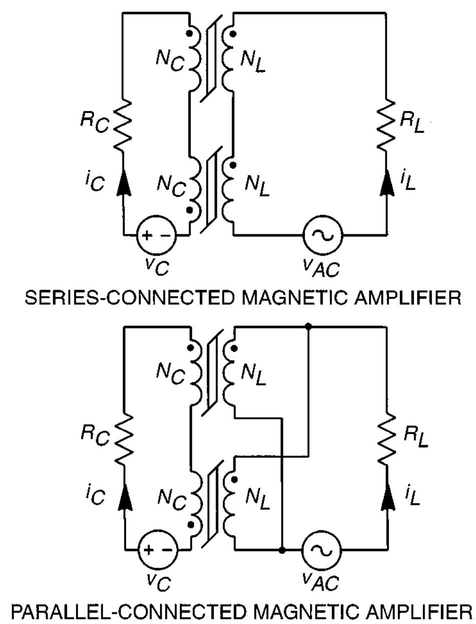

Fig. 8. As the average value of the dc control current i_C in the series- or parallel-connected magnetic amplifier varies due to a change in v_C or R_C, the half-cycle average value of the load current i_L varies proportionally.

current i_C flowing in the series-connected control windings. As the dc current i_C in the control windings varies, so does the ratio of the time during each half cycle of the ac source that one or the other of the magnetic cores operates on a low-inductance saturated segment of its characteristic to the time both cores operate on their high-inductance unsaturated segments. The pair of saturable reactors behaves like a controllable inductive reactance switching rapidly once each half cycle between a high and a low differential inductance. The resulting waveforms shown

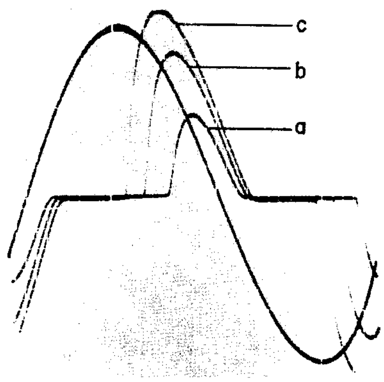

Fig. 9. Series-connected magnetic amplifier. Waveforms of v_{AC} and of i_L for three increasing values of v_C.

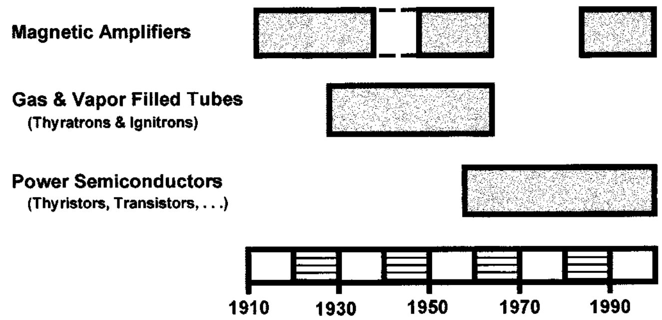

Fig. 10. Three mainstreams in the evolution of power electronics.

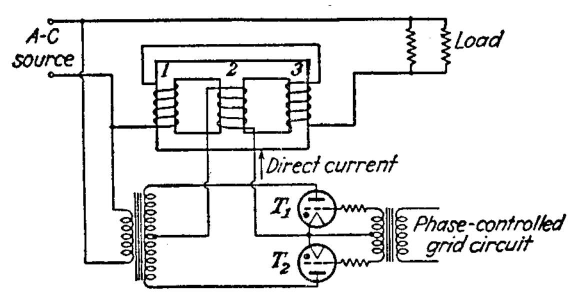

Fig. 11. Reproduction of [12, Figs. 11–55] with original caption, "Circuit for controlling an alternating current by means of thyratrons and saturable reactors."

in Fig. 9 are very similar in appearance to those observed with a triac controller as a result of changes in triac resistance that occur during a cycle.

The circuits in Fig. 8 are ac-to-ac power converters. They are very rugged and contain no heaters, filaments, or moving parts. They are highly efficient and their size and weight decrease, as the frequency of the ac source increases. They are also capable of high power output as will be described. In short, the magnetic amplifier is a very effective power electronic circuit.

Some five years before Alexanderson's magnetic amplifier work, Dr. L. DeForest in 1907 invented the three-element thermionic vacuum tube. This device differs from the magnetic amplifier in significant ways. The natural power source for this device is a dc voltage not an ac one as is the case for magnetic amplifiers. Because vacuum tubes can use batteries for their power source, they are far more attractive for portable applications than magnetic amplifiers. The nonlinear switching element is a resistive element that changes from a large value of resistance to a small value under control of voltage applied to one of its terminals called the grid. Among his other contributions, DeForest discovered that, by the application of feedback from the plate to the grid of his triode, he could cause self-regenerating oscillations which could serve as a high-frequency source for modulating voice and other communication signals. Magnetic amplifiers, on the other hand, are incapable of self-oscillation.

By 1916, Alexanderson's magnetic amplifier had been used to modulate as much as 70 kW of power, while Dr. DeForest's three-element thermionic vacuum tube was able to handle only a few tens of watts. It was in this year that Alexanderson achieved a major triumph by using his magnetic amplifiers to establish the first radio link between the United States and Europe. Some of the work leading up to this achievement is reported in a paper by Alexanderson and Nixdorff [13] and ends with an interesting exchange between DeForest and Alexanderson reflecting the state of the art at the time.

The history of the technologies prominently employed in power electronics divides into three overlapping periods as indicated by the three time lines in Fig. 10. Although restricted largely to low-power applications, World War I and the decade of the 1920's saw rapid development of vacuum tubes with truly phenomenal performance that soon overshadowed the solid virtues of magnetic amplifiers for most low-power applications. The period between 1928 and 1933 saw the development of gas- and vapor-filled controlled rectifiers, developed specifically with higher-power applications in mind. Prominent among the new devices were two controlled rectifiers—the *gas-filled thyratron* and the *mercury-arc ignitron* [15]. In both of these, a unidirectional current with a relatively low voltage drop flows after an enabling signal is applied to a third electrode that allows the gas discharge to start. In the case of the thyratron, the function of the grid is to prevent the initiation of an arc from anode to cathode until a preselected time in the cycle. In the case of the ignitron, reported upon in 1933 by Slepian and Ludwig [16], a pulse of current through the third electrode, called an igniter, initiates a cathode spot on the pool of mercury at the beginning of each conduction period.

As one might suspect, numerous applications combined controlled-rectifier tubes and magnetic amplifiers. One such application was the stepless variation of theater-stage and auditorium lighting as shown in Fig. 11 [15]. A few watts expended in the grid circuit of two thyratrons in a push-pull connection provided the variable dc current to control the much larger magnetic-amplifier-output current to the lighting loads.

Although there were notable exceptions, throughout the 1930's until the late 1940's the popularity of magnetic amplifiers waned and that of tube controlled rectifiers rose. The term *industrial electronics* became popular to describe the high-power applications of electronics for other than communication purposes.

By the time of World War II, there was another power amplifier that should be mentioned that saw a great deal of service. It was a rotating amplifier called the *Amplidyne* or *Rototrol* which was effectively a combination motor-generator with no rotating shaft brought to the outside. Such a device, because of its nonstatic electromechanical nature, however, falls outside our definition of an electronic power conditioner.

An interesting turn of events came during World War II. On May 18, 1941, the newly commissioned German heavy cruiser *Prinz Eugen* accompanied the awesome new battleship *Bismarck* as the two slipped out of the Baltic Sea to prowl the Atlantic shipping routes. Some historians consider the nine days that followed to be the most thrilling of the long war in the Atlantic. On the sixth day out, the veteran British cruiser *Hood* was sunk in a three-minute engagement and the new not-fully-equipped battleship *Prince of Wales* was severely crippled. Three days later, with the combined help of the captured German code machine ENIGMA, a U.S. Navy Ensign named Smith, and a rapidly assembling fleet of British war vessels, the most powerful ship afloat, the *Bismarck,* was sunk. The *Prinz Eugen* broke away and was one of the few main-line German ships that survived the war. When the *Prinz Eugen* did fall into Allied hands you can well imagine the interest with which Allied Intelligence swarmed over the ship. When they did, they were unable to locate the fire control equipment for controlling the ship's 8-inch guns. No one seemed to know where the equipment was. Finally they located a Chief Petty Officer who had been with the *Prinz Eugen* since her commissioning; and he said, pointing to some steel plates that had been welded shut, "Oh yes, it is behind these plates." For the Allies, keeping fragile electronic equipment operative on fighting vessels had been a constant major problem throughout the war. And here, the Germans had not even looked at their equipment since the ship was commissioned [17]. The technology the Allies found behind these steel plates immediately became classified and remained so for several years.

The Germans were using *magnetic amplifiers.* They were using these devices not only in the Navy, where it was a common occurrence for them to operate without attention for the life of the vessel; but they also were using magnetic amplifiers in a wide range of applications from stabilizers for range finders and gun mounts, to the steering of the buzz bombs and V-2 rockets that were showered on England toward the end of the war [18].

During the 1930's, Frank G. Logan, an engineer at Vickers Electric in St. Louis, Missouri patented nineteen improvements to magnetic amplifiers by coordinating the nonlinear switching effect in the magnetic cores with the change in resistance of rectifiers between forward conducting and reverse blocking states [19], [20]. The result was considerably higher power gain with simpler circuit configurations. Such circuits are called self-saturating magnetic amplifiers.

German success had come by taking these new circuits which had not received much attention in the United States and using them with new square-loop magnetic materials such as Orthonol and permalloy which the Germans had developed along with much improved dry type copper-oxide and selenium rectifiers. The result was spectacular, and power electronics as a result took a major step forward in the late 1940's and throughout the 1950's. Magnetic amplifiers became the equipment of choice for rugged reliable military and industrial-control applications.

Another, major and *unanticipated* course change for power electronics was again just around the corner. This was the invention and development of controllable semiconductor devices. In 1948, the point-contact transistor was invented at Bell Laboratories, soon to be followed in 1951 by the invention of the junction transistor. The first power semiconductor was the silicon controlled rectifier (SCR) or thyristor developed by General Electric Corporation in 1957 and made commercially available in 1960 and 1961. Because these events are more recent and there are many excellent books and articles that review the development of power semiconductor devices, including two excellent IEEE Press books one edited by Bose [21] and the other by Thollot [22], this seems a fitting point at which to end this brief historical review.

The time lines shown in Fig. 10 indicate periods of wide spread acceptance and applications of three different power electronics technologies. Fig. 12 attempts to show on a single time line a concise picture of the seminal events surrounding the evolution of power electronics. The top row of boxes in Fig. 12 shows critical events related to the development of magnetic amplifiers. The second row of boxes shows key events that impacted the development of vacuum and gas or vapor filled tubes. The four boxes to the left in this row do not fall within the scope of the definition given for power electronics. The two boxes to the right do meet all of the conditions set forth for power electronics equipment. In the third row of boxes for semiconductors, the bold lines signify devices employed as switching elements in power electronics equipment.

Some mention has been made of events related to all of the boxes in Fig. 12 except for the three at the left in the second row. The left-most box refers to the discovery by Thomas A. Edison in 1883 of what is today referred to as thermionic emission or the *Edison effect.* It states that *when a voltage of proper polarity is applied between two electrodes, one hot and one cold, that are placed in an evacuated enclosure, current flows in an external circuit joining the two from the hot to the cold element.* The Edison effect remained unexplained for almost two decades until 1901 when the results of investigations by O. W. Richardson and colleagues were published. The rectification property of *thermoelectric vacuum diodes* was first used by J. A. Fleming in 1904 for the reception of radio signals.

Around 1900, P. Cooper-Hewitt expanded his talents in the manufacture of mercury-vapor lamps to exploiting the unidirectional properties of the mercury arc and applying them to the task of rectification [23]. He evolved the basic form of the glass bulb *mercury-arc rectifier* and established the road map for the future development of steel-tank rectifiers capable ultimately of conducting tens of thousands of amperes with voltage drops of 30 to 40 V. The mercury-arc rectifier is truly an impressive power-handling device but it is not controllable. Controllability of the mercury arc had to wait until 1933 when Slepian and Ludwig described the ignitron. The *ignitron* is a mercury-pool cathode device with a pointed tip ignitor immersed in a mercury pool such that a pulse of current applied to the ignitor when the anode is positive starts an arc between the cathode and the anode. As early as 1903, Cooper–Hewitt foresaw the possibility of controlling a mercury-arc discharge by applying voltage pulses to a grid located between anode and cathode. Al-

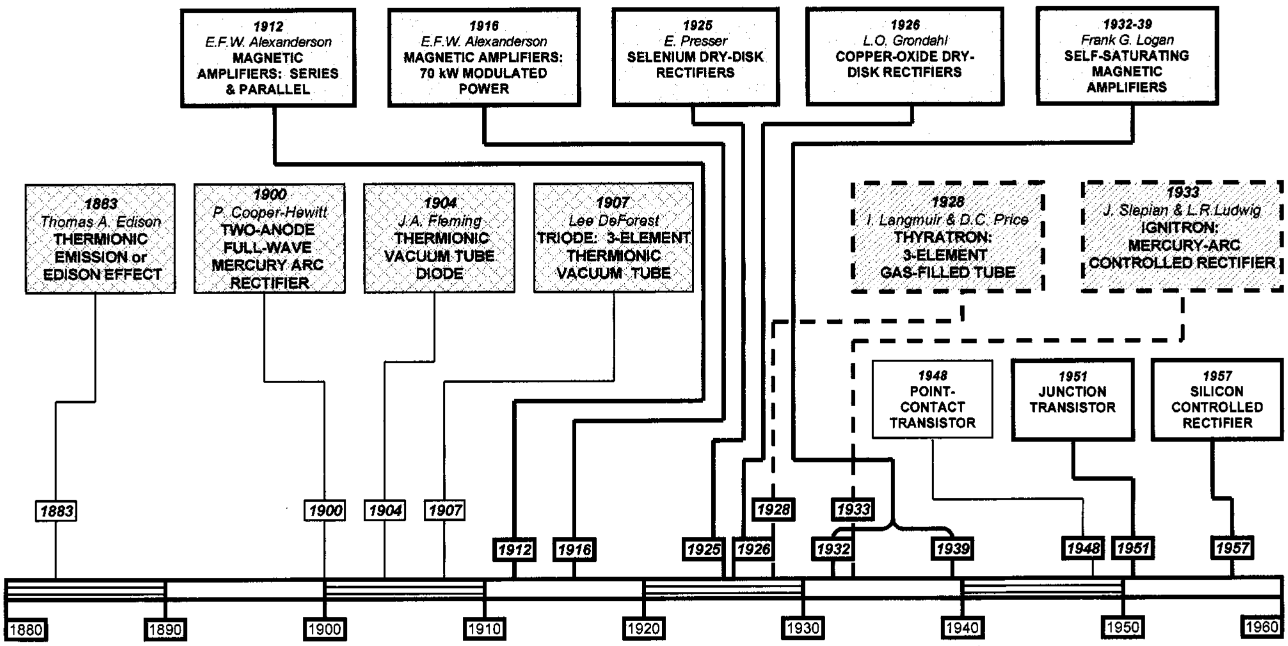

Fig. 12. Time line surrounding evolution of power electronics.

though many approaches were pursued, it is generally agreed that Langmuir and Prince developed the first practical mercury-vapor rectifier incorporating a control grid in 1928. Named a thyratron, it is a gas triode with a hot or thermionic cathode. Negative voltage on the grid prevents the formation of plasma between anode and cathode until a trigger pulse sufficiently reduces the negative grid bias and allows anode current. Once conduction starts, grid voltage has no influence on the anode current.

IV. Conclusions

In this paper, we provide what we hope is a meaningful definition of power electronics. The definition offered includes for two reasons the phrase "by static means." One is rather obvious, and that is to exclude equipment that intimately depends on components employing moving parts and mechanical switching. The other is perhaps less obvious; it is to allow the inclusion of magnetic amplifiers under the category of power electronics equipment.

In all but one aspect, magnetic amplifiers seem to more than satisfy all of the goals, requirements, and objectives set forth for power electronics equipment. The one place that a magnetic amplifier may fall short is that, as can be seen in Fig. 8, a magnetic amplifier does not need to contain any *electronic* device as such. The term power electronics came into wide acceptance as the umbrella term to describe the field during the late 1970's, by which time semiconductors had been the almost universal choice to perform the requisite switching-impedance function for a decade and a half. In the mid 1980's and up to the present, magnetic amplifiers began experiencing a comeback to the power electronics field, not for just certain control functions, but as the active switching-impedance device in many high-frequency switching power supplies [24], [25]. It would seem a shame not to include them in the brotherhood of power electronic devices.

In addition to defining power electronics, we highlight some of the special attributes that set these circuits apart from other electronic equipment. We also identify some of the fundamental technological differences among the four classifications of power converters.

To this point in time, the field of power electronics can be viewed as having three identifiable mainstreams of development in its evolution. They are magnetic amplifiers, gas-tube and vapor-tube controlled rectifiers, and power transistors and semiconductor controlled rectifiers. As here briefly illustrated, power electronics has had a long and rich history, even if a somewhat obscure one. If the past in any indicator, many of the future contributions to the field will continue to result from unanticipated breakthroughs in materials and devices that are creatively applied to control and process the flow of electrical energy.

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