AC Adjustable-Speed Drives at the Millennium: How Did We Get Here?

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Invited Paper

Abstract—Although there is broad recognition of the huge strides taken in the development of modern ac adjustable-speed drives since the introduction of the thyristor in 1957, far fewer engineers in the power electronics profession today are aware of the key engineering developments in this field that preceded the solid-state era. The purpose of this paper is to review major milestones that set the stage for the development of today's ac drives, including sufficient details to acquaint readers with their basic principles, strengths, and limitations. Attention will be devoted to the continuum of this development history and the many direct echoes of developments from the first half of the 1900s that we take for granted in today's ac drives. In addition, the spirited competition between electromechanical and electronic ac drive solutions that dominated engineering attention during the early part of the century will be reviewed, highlighting the complicated interrelationship between electric machines and drive electronics that persists today.

Index Terms—AC motor drives, cycloconverters, history, ignitrons, inverters, mercury-arc rectifiers, thyatrons, variable speed drives.

I. INTRODUCTION

A. Overview

THE large majority of power electronics engineers active in the profession today began their careers after the commercial introduction of the silicon thyristor in 1957. During the subsequent solid-state era, we have collectively witnessed incredible progress in the development of ac adjustable-speed machine drives with ratings from microwatts to multimewatts. However, the history of ac drives extends long before the invention of the thyristor, including key fundamental developments in the late nineteenth century. In fact, many of the basic concepts and circuits embedded in today's ac adjustable-speed drives trace their origins directly to the pre-thyristor period. This observation makes it all the more unfortunate that our collective first-hand memories about this crucial developmental period are progressively fading as we enter the new millennium.

The purpose of this paper is to review key developments in the history of ac adjustable-speed machine drives, focusing on

major trends and breakthroughs that occurred during the first half of the twentieth century preceding the thyristor's arrival. In so doing, an attempt will be made to expose the technological roots that underlie many of the key concepts that form the heart of modern solid-state ac drives. Despite all of the incredible technological progress since the introduction of the thyristor, some of the key hurdles that challenged drive development engineers in the first half of the 1900s bear a very direct relationship to the problems that the current generation of drive engineers struggle with today.

B. Background and Paper Structure

The history of electronic power conversion during the first half of the century is tightly intertwined with the development of electronic triggered-arc power switch technology. Just as we revel in the possibilities created by new classes of power semiconductor switches today, the introduction of the mercury-arc rectifier, thyatron, and ignitron [1]–[3] each marked a major milestone in the development of electronic power converters during the first half of this century.

However, each of these new triggered-arc switches was also characterized by important performance limitations that bounded its range of usefulness. Recognizing that today's electrical engineers are seldom introduced to these devices at all, information is provided in Section II to acquaint readers with the basic operating characteristics as well as the strengths and limitations of the major families of these triggered-arc devices.

While acknowledging the significance of these arc switch developments, it would be hard to underestimate the importance of innovative electromechanical solutions that were developed during the first half of the century to provide speed adjustability for ac machines without the use of any electronics. Section III of the paper provides a summarized overview of these electromechanical configurations, providing the backdrop for the later introduction of electronic ac drives.

Progress in the development of high-power triggered-arc switches during the 1920s and beyond set the stage for a classic confrontation between electronic and electromechanical solutions to the problem of ac machine speed control. A flood of new ac drive power circuits, controls, and systems technology followed closely on the heels of the power switches themselves, and Section IV highlights some of the most notable accomplishments.

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C. Past Contributions and Caveats

This paper makes no attempt to provide a comprehensive scholarly treatment of the history of ac adjustable-speed drives. Such a work apparently does not exist at this time. However, acknowledgment must be given to several valuable papers and bibliographies contributed by specialists in this field that, collectively, tell much of the story of this important and fascinating technology development from an engineering perspective [4]–[8]. This paper is intended to build on these past works, focusing on the associated engineering issues.

Given the finite length of this paper, attention has been focused on a limited number of technological highlights in the development of ac adjustable-speed drives. The authors regret any unintentional historical oversights or inaccuracies that appear in this manuscript.

II. TRIGGERED-ARC POWER SWITCHES

A. Controlled Mercury-Arc Rectifiers

The development of electronic power switches based on the control of gaseous arc discharges for current conduction and rectification has an intriguing history that, regrettably, must be highly condensed in this paper. Application of electrical arcs using liquid mercury (Hg) electrodes for lighting dates back to the 1850s. The ability of mercury electrodes to rectify electrical arc discharges was recognized as early as 1882 by Jemin and Meneuvrier [9]. The desirable effects of reduced atmospheric pressure on the characteristics of this discharge were recognized in the early 1890s [10].

Peter Cooper Hewitt is considered to be the first to apply the mercury-arc discharge principles for the explicit purposes of electrical rectification in 1901 [11]. Uncontrolled mercury-arc rectifiers (i.e., without control grids) were developed in the form of evacuated glass bulbs and pumped steel tanks during the next 30 years for use in a range of applications including electric traction and battery chargers for electric vehicles.

The concept of introducing a grid between the anode and mercury-pool cathode to control the instant of arc initiation was patented by Irving Langmuir in 1914 [12]. However, several years elapsed before this technology was successfully introduced into pumped steel tank mercury-arc rectifiers by several major manufacturers in the late 1920s.

Development of large steel tank controlled mercury-arc rectifiers progressed rapidly during the 1930s, with units rated for as much as 16 kA at 500 V reported by 1935 [1]. Voltage ratings as high as 30 kV were available in this same time frame. A cross section of a typical steel tank unit is provided in Fig. 1. A notable characteristic of these units is that they were typically designed with several (often 12 or more) independent anodes and a shared mercury-pool cathode. As ratings grew, so did the size and weights of the rectifiers, with tank heights and diameters exceeding 3 m in large units.

The forward voltage drop of a mercury-arc rectifier depends on the anode-cathode separation distance which, in turn, depends on its electrical ratings. Forward voltage drops in the range of 25 to 40 V were typical for these units. Since the associated losses of large units might fall in the range of 20 to

Fig. 1. Cross section of Allis Chalmers controlled-grid pool-cathode mercury-arc rectifier [18].

100 kW, high-capacity water cooling systems were typically required to keep the anode plates of the rectifiers within their safe limits of 50 °C to 75 °C [2]. Vacuum pumping also required significant amounts of additional equipment, adding both volume and weight to the installation.

Deionization times for these mercury-arc rectifiers, representing the minimum time required for them to regain their blocking state following current removal, were typically in the range of 100 μ s. The negative grid voltage necessary to prevent rectifier conduction was typically in the range of –20 to –50 V, and the threshold for triggering forward conduction depended on the instantaneous forward anode-cathode voltage, making precise control of triggering times difficult. Auxiliary excitation anodes were necessary to maintain an active arc to the rectifier cathode at all times, insuring that the unit would be ready to operate following periods of light or zero load.

A significant problem with mercury-arc rectifiers was their vulnerability to various types of transient short-circuit faults. Not only were they vulnerable to misfires in the forward voltage blocking condition (directly analogous to shoot-through faults in thyristors), they also suffered from intermittent short-circuit faults in the *reverse-conducting* (cathode-to-anode) direction known as arc-back (or backfire) faults. Development of such faults typically required immediate opening of circuit breakers to restore normal operation, although arc suppression techniques using the grids were eventually developed to minimize the need for breaker activation under many operating conditions [41]. Much effort was devoted to designing rectifier units to

Fig. 2. Sketches of two different early designs of GE hot-cathode thyratrons [14].

minimize the occurrence of such faults, but they were never entirely eliminated as a problem.

B. Thyratrons

In parallel with the evolution of the pool-cathode mercury-arc rectifiers, the development of electronic vacuum tubes using thermionic emission from heated filament cathodes led to a distinct family of triggered-arc switches known as thyratrons. Following DeForest's invention of the thermionic triode vacuum tube in the early 1900s, attempts were made to apply these principles to power control applications. Work at GE led to the development of the high-voltage "pliotron" triode vacuum tube that was used in some of the earliest inverter developments [13].

It quickly became clear that use of thermionic emission in high vacuums for power control applications would be highly restricted because of the high forward voltage drops (in the range of hundreds of volts) necessary to achieve very modest current densities [14]. This led workers at GE to introduce a low-pressure mercury atmosphere into the triode tube creating the thyatron, combining the advantages of thermionic emission with arc-discharge conduction. The thyatron was announced to the world in 1928 [15], very close to the same time that grid-controlled pool-cathode mercury-arc rectifiers became available.

Cross sections of two glass-envelope thyratrons are provided in Fig. 2 (metal case versions were also manufactured). Since the thyatron ultimately depends on a mercury arc for its operation, its performance characteristics have much in common with the pooled-cathode devices described above [14]. However, there are some important differences that are worth noting. The forward voltage drop of the hot-cathode thyratrons (12 to 15 V) was approximately half that of the cathode-pool mercury-arc rectifiers, making the thyatron particularly attractive for lower voltage (<500 V) applications. Grid blocking voltages tended to be in the same ranges as those noted above for pool-cathode units.

Although thyatron power ratings gradually increased during the 1930s, they never caught up with the ratings of their pool-cathode counterparts. By the middle of the 1930s, commercial units capable of handling at least 1000 A and 15 000 V were being offered [1]. Forced-air cooling was typically sufficient for these devices, and temperature limits were very similar to those of the pool-cathode units (50 °C to 70 °C).

Thyratrons were subject to the same classes of forward- and reverse-conducting faults as the pool-cathode rectifier units. Just as in the pool-cathode units, design improvements significantly reduced the frequency and severity of such faults as the years passed, but they were never totally eliminated as a practical problem [40].

C. Ignitrons

The ignitron was developed by Joseph Slepian and his colleagues at Westinghouse in 1933 [16]. It is a form of pool-cathode mercury-arc rectifier that replaced the control grid with a special ignitor rod extending into the cathode mercury pool to trigger the anode-cathode arc each cycle. Application of a very short voltage pulse to the ignitor was sufficient to initiate the arc, eliminating the need for a permanent "keep-alive" excitation anode.

The nature of the arc ignition in an ignitron made it unsuitable for multi-anode configurations, in contrast to the grid-controlled units. As a result, ignitrons were typically packaged as single-anode units using either pumped tanks or newer sealed metal cases that were perfected during the 1930s [17]. A cross section of a pumped water-cooled unit is provided in Fig. 3 [18].

The closer spacing between the anode and cathode in typical ignitron designs made it possible to reduce its forward voltage drop compared to the multianode pool-cathode rectifiers. As a result, ignitrons were attractive for high-power applications at lower voltage levels (e.g., 3000 V). In other regards, the ignitron exhibited many of the same operating characteristics as the controlled-grid rectifiers and thyratrons described above, including vulnerability to transient short-circuit faults in both current polarities [39].

III. ELECTROMECHANICAL AC DRIVE SCHEMES

A. Overview

Although induction motors quickly grew in popularity for industrial applications during the early years of this century, their torque-speed characteristics limited their usefulness to constant-speed operation when excited from fixed-frequency utility sources. As a result, large amounts of development effort were invested around the world in finding effective ways to vary the speed of ac machines. In the absence of mature power electronics, electromechanical techniques dominated the approaches that were widely implemented during the first half of the 1900s.

Technical papers presented by Maier [19] and Crosby [20] in 1911 and 1914, respectively, provide interesting contemporary summaries of ac machine speed control technology during this era. Several of these techniques were widely used for several more decades [21] before the arrival of mature thyristor-based ac drives in the 1960s and 1970s, and some still survive today

Fig. 3. Cross section of Westinghouse single-anode pumped-tank ignitron [18].

in adapted forms. The most important of these approaches are summarized in the following paragraphs.

B. Wound-Rotor Induction Motor Control Techniques

The wound-rotor induction motor is a particularly attractive candidate for adjustable-speed control because only a fraction of the output power must be handled by the rotor windings brought to the outside world via slip rings. Changing the voltage applied to these terminals using any of a variety of techniques provides an effective means of varying the speed of the machine.

The power delivered at the rotor terminals of the wound-rotor machine, P_r , is directly proportional to the difference between the synchronous and actual rotor speed for a constant output torque. Thus, achieving progressively wider speed range requires the rotor circuit to handle increasing amounts of power.

The frequency of the rotor circuit voltages and currents is the difference between the stator excitation frequency ω_e and the rotor frequency ω_r , an important variable known as the slip frequency ω_{sl} (all three frequencies in elec rad/s). The machine can be operated at speeds above the synchronous speed (super-synchronous operation) provided that an external source is available to deliver power at the appropriate slip frequency into the rotor circuit.

1) *Kramer System*: Since basic techniques such as pole-changing can only provide a very limited number of discrete rotor speeds, intensive efforts were made during the first decade of this century to develop techniques that would provide a wider and continuously-variable range of rotor speeds. Use of variable resistors connected to the rotor terminals of the wound-rotor machine provides one of the simplest means of

Fig. 4. "Constant-horsepower" Kramer system configuration [43].

adjusting its speed, but the power dissipated in those resistances reduces the system's efficiency significantly.

One of the most successful approaches that avoids such losses was the Kramer system [22] announced in Germany in 1906. Although many versions of this scheme were eventually developed, one of the most basic of these is shown in Fig. 4. This "constant-horsepower" version requires the addition of a dc motor directly coupled mechanically to the wound-rotor induction motor, plus a third machine to serve as an ac-to-dc rectifier.

The machine that provides this rectification function, known as a rotary converter, is a fascinating machine that has many of the structural features of a shunt-field dc motor, including brushes, commutator, and armature windings. However, it also has multiple (typically three) taps on the armature windings that are brought to the outside world via slip rings. By properly spacing these taps on the armature windings for balanced three-phase excitation, this machine performs as an electromechanical rectifier to convert the ac rotor power (at the slip frequency $\omega_{sl} = \omega_e - \omega_r$) into dc that can be used to excite the dc motor [23]. The mechanical output power of the dc motor is directly added to that of the wound-rotor induction motor. Speed is adjusted by varying the field excitation of the dc machine.

2) *Scherbius System*: A major alternative to the Kramer system for wound-rotor induction machine drives was the Scherbius system, introduced in Germany in 1907. Many different variants of the Scherbius system were eventually developed, similar to the situation described above for the Kramer system. Fig. 5 shows a "constant-torque" version of the Scherbius system in which the rotor power from the wound-rotor induction machine is fed back to the ac power grid at 50/60 Hz rather than being converted into mechanical power.

A key element in this Scherbius configuration is the three-phase ac commutator motor that converts the ac rotor power into mechanical power to drive the ac alternator connected to the utility grid. This is a commutator machine that has been modified specifically for polyphase ac excitation with a three-phase distributed stator winding and three sets of brushes spaced at 120 electrical degree intervals around the commutator. Development of both three-phase and single-phase ac commutator machines was aggressively pursued during the early years of

Fig. 5. "Constant-torque" Scherbius system configuration [43].

the century with their largest impact in railway traction systems using low-frequency ac excitation at 16-2/3 or 25 Hz.

The frequency of the ac commutator machine's excitation is the slip frequency ω_{sl} which must be limited to 25 Hz or less to insure good commutation, thereby limiting the minimum practical speed of such a system. Speed control is achieved by adjusting the field excitation using an adjustable transformer.

Although the Krämer and Scherbius systems each provided unique system features, their costs were roughly comparable for the same motor speed range. Both were widely used around the world for many industrial applications extending into the megawatt range. The rating, size, weight, and cost of the auxiliary machines in the rotor circuit are determined by the desired induction motor speed range that, in turn, determines the amount of rotor power P_r that must be processed. Economic considerations typically limited the lower limit of the drive's speed range to 50% of the wound-rotor machine's synchronous speed.

3) *Schrage Brush-Shifting Motor*: Since a major disadvantage of the Krämer and Scherbius systems is their need for expensive auxiliary machines, it is not surprising that significant effort was invested in exploring techniques for combining these auxiliary machines into the same electromechanical structure as the main wound-rotor induction motor. The most successful of these integrated configurations was the Schrage motor [24], another German development that was first introduced in 1914.

Fig. 6 provides a winding diagram of this rather complicated but ingenious machine. The Schrage motor actually combines an inside-out wound-rotor induction machine with a frequency changer machine that shares many of the same physical features as the rotary converter machine discussed previously. The rotor-mounted primary windings are excited from the utility grid via slip rings, and the commutator connected to the rotor-mounted adjusting winding converts line frequency ω_e to the lower slip frequency ω_{sl} that excites the stator-mounted three-phase secondary windings. Speed amplitude and polarity are adjusted by mechanically shifting the angular positions of the brushes. Speed ranges of six to one can be conveniently achieved using this type of machine.

Although there is no firm upper limit on the power ratings that can be achieved using Schrage motors, they proved to be most practical for ratings of 50 kW or less. These units were

Fig. 6. Schrage brush-shifting motor winding configuration [44].

widely used in industrial applications such as textile mills well into the 1960s [25] when the availability of solid-state inverter drives gradually began to displace them from their established market positions [26].

IV. EARLY ELECTRONIC AC DRIVES

A. Overview

The preceding section provides a sketch of the established electromechanical ac drive technology against which early power electronic drives were forced to compete during the first half of the twentieth century before the arrival of mature thyristor-based drives in the 1960s.

Technical breakthroughs with vacuum tubes and triggered-arc switches combined with the recognized limitations of the prevailing ac drive technology attracted the attention of top researchers in the power field from around the world. As a result, the years between 1910 and 1940 were incredibly productive in defining many of the fundamental building blocks of electronic ac drive technology that are still with us today, appropriately adapted for solid-state drives.

In particular, the introduction of triggered-arc switches spurred the rapid development of a broad range of basic power circuit topologies and techniques that are often taken for granted today, including phase control, natural commutation, forced commutation, dc-to-ac inversion, cycloconversion, and many others. Fundamental similarities between the operating characteristics of triggered-arc switches and thyristors made the extension of these underlying concepts into the solid-state world almost seamless.

Unfortunately, early power electronics technology based on the triggered-arc power switches described in Section II was burdened with its own set of significant disadvantages that prevented it from successfully competing with the established electromechanical ac drive solutions in most ac drive applications. As result, there were quite a number of impressive technical accomplishments with early electronic ac drive systems that never achieved commercial success against electromechanical competitors during the professional careers of their developers.

E. F. W. Alexanderson, one of the most prolific of these inventors, recognized this reality in 1938 [27] when he wrote:

Fig. 7. Electronic Krämer drive using uncontrolled rectifier bridge [27].

"(t)here is, however, as yet, no adjustable-speed ac motor so flexible as the Ward-Leonard combination, and there is still room for much improvement in adjustable-speed a-c motors."

Looking back, it is apparent that many of the key innovations were ideas ahead of their time that had to await the arrival of solid-state power electronics technology thirty or more years later to make them practical.

B. Electronic Wound-Rotor Induction Motor Drives

In view of the attractive features of the electromechanical drive solutions for wound-rotor induction motor drives, it seems natural that effort would be invested in developing electronic counterparts. For example, Fig. 7 shows a diagram of an electronic Krämer drive system discussed by Alexanderson *et al.* in 1938 [27] that replaces the electromechanical rotary converter in the classic Krämer system (Fig. 4) with a static uncontrolled rectifier using power tubes.

A year later in 1939, Stöhr in Germany discussed electronic counterparts to the classic Scherbius system that was presented earlier in Fig. 5 [28]. One version of this electronic Scherbius drive shown in Fig. 8 uses two grid-controlled pool-cathode mercury-arc rectifiers to form a controlled rectifier-inverter combination to convert the machine's rotor power (at slip frequency) into utility grid power. This static converter equipment directly replaces the combination of ac commutator motor and ac alternator required in the electromechanical version, eliminating the need for its attendant electrical/mechanical energy conversions.

Although electronic versions of the Krämer and Scherbius drive systems achieved only limited commercial success using any of the triggered-arc power switches, their usefulness was ultimately vindicated 25 years later when high-power thyristors made them appealing drive solutions for a variety of industrial applications.

Fig. 8. Electronic Scherbius drive using rectifier-inverter combination [28].

C. Electronic Synchronous Machine Drives

Interestingly, the synchronous machine received serious attention as a candidate for adjustable-frequency *stator* excitation using electronic switches earlier than induction motors. There was a clear and long-standing fascination with the concept of using the electronic switches to replace the mechanical commutator of a conventional dc machine, and the synchronous machine with its electronic drive was often referred to as a commutatorless motor to emphasize this perspective.

Attempts to find workable approaches for achieving this commutatorless motor began early in the century before thyatrons or controlled-grid mercury-arc rectifiers were even available. For example, a concept developed by A. Bolliger in 1917 and published in 1921 [29] proposed to implement the electronic commutator using a combination of mechanical switches and a multianode pool-cathode mercury-arc rectifier without control grids.

More practical and successful attempts to realize workable commutatorless motor drives came during the late 1920s and early 1930s following the introduction of the triggered-arc power switches. Two of the configurations that were successfully developed for industrial and traction applications deserve attention here. Both use a form of direct ac-to-ac cycloconversion with natural commutation to convert the utility power at line frequency to polyphase excitation at a lower frequency to excite the machine's stator windings. Self-synchronization of the excitation with the rotor position, a prerequisite for successful operation of any such system, was achieved using a "distributor" mechanism mounted on the rotor shaft to excite each phase during the proper angular intervals.

E. Kern and Brown Boveri engineers developed a synchronous motor drive for railway traction applications using excitation from a single-phase ac (25 to 60 Hz) power distribution system [30], [31]. As shown in Fig. 9, the drive was configured to use a multi-anode grid-controlled mercury-arc rectifier to excite the 12 machine stator windings. This system was installed in a number of European locomotives with ratings that reached at least 2400 kW by 1935 [2], built using four 600-kW commutatorless machines.

Significant efforts were also made by E. Alexanderson and his colleagues at GE during the 1930s to develop another version of this synchronous motor drive using thyatrons for industrial applications [32], [33]. A diagram of this "thyatron motor" is

Fig. 9. Brown Boveri commutatorless motor drive configuration [31].

Fig. 10. Thyatron motor configuration [32].

provided in Fig. 10, showing the 18 thyatrons needed to excite the six stator windings from a three-phase utility source. The first successful field application of this system was a 375 kW unit that went into service in 1936 as a fan drive for a utility power plant boiler [34]. The high number of tubes represented a cost disadvantage, but this was offset somewhat by the drive's ability to continue operating following failures of one or more individual tubes. Interesting features of this system included

Fig. 11. Early load-commutated inverter (LCI) synchronous motor drive [28].

Fig. 12. Variable-ratio naturally-commutated cycloconverter synchronous motor drive [28].

“hot-swapping” of failed thyatron tubes during operation for improved drive availability that reached 96.5% during the first 14 months of operation.

Although these synchronous motor drives represented one of the most significant commercial successes for electronic ac motor drives prior to the arrival of the thyristor, they never seriously challenged the electromechanical drive solutions discussed previously in Section III. On the other hand, it was during this productive period in the 1930s that the concepts for load-commutated inverter (LCI) synchronous motor drives were formulated, including the recognizable version in Fig. 11 presented by Stöhr in 1939 [28]. These LCI drives later became highly successful in the 1970s for high-power industrial drive applications using thyristors to replace the triggered-arc power switches.

D. Cycloconversion

Establishment of the key concepts for direct ac-to-ac cycloconversion using naturally-commutated switches proceeded quite rapidly during the early 1930s. Early schemes were intended for and limited to conversion between two frequencies at a fixed integral frequency ratio (typically 3:1 for railway 50-to-16-2/3 Hz power conversion). However, a technique for “asynchronous” cycloconversion between two frequencies at continuously-variable frequency ratios was announced by M. Schenkel and I. von Issendorf in 1931 [35].

Versions of variable-ratio cycloconverters were developed using both pooled-cathode mercury-arc rectifiers [1] and for single-anode switches (such as ignitrons). Proposals were soon developed for applying these cycloconverters to ac motor drives, either for direct stator excitation (see Fig. 12) or for rotor power conversion in wound-rotor induction machine drives. However, there is little evidence that such schemes ever achieved significant commercial usage for ac drives during this time due to the large number of required switches and rather complicated controls. Here again, commercial success awaited the arrival of the thyristor.

Fig. 13. Self-commutation concept from Mittag patent [36].

E. Auto-Sequentially Commutated Current-Source Inverters

Since induction machines draw reactive power with a lagging power factor from their ac sources, they present basic compatibility problems with naturally-commutated inverter topologies such as the load-commutated inverter described above for synchronous machines. Although virtually all of the discussion in this section has focused on naturally-commutated power circuits, it is important to note that concepts for forced-commutation of triggered-arc power switches using capacitors were established quite soon after the introduction of the switches themselves in the late 1920s [15]. These concepts were progressively enhanced during the following years.

A patent issued to A. Mittag of GE in 1934 [36] contains an important enhancement aimed at improving the ability of the main switches (marked 17 and 18 in Fig. 13) to commutate each other when they are alternately triggered by strategically introducing diodes 19 and 20. This disarmingly simple modification provided the foundations for the three-phase auto-sequentially commutated inverter (ASCI) using thyristors [37].

Although there is no evidence that Mittag's original versions of this inverter for ac motor drives were broadly utilized during his career, the derivative ASCI induction motor drives were widely adopted for industrial applications during the 1970s. As a result, current-source inverter schemes for induction motor drives competed seriously in the marketplace with their voltage-source counterparts until new power devices eventually became available (e.g., GTOs, IGBTs) that could be conveniently turned off from their control terminals.

V. CONCLUDING COMMENTS

Looking back over the rich tapestry of technical achievements summarized in this paper, it is very clear that the history of electronic ac machine drives began long before the commercial introduction of the thyristor in 1957. The list of key principles of power electronics and ac drives that were established during the early decades of the century is truly impressive, and our respect for the many associated inventors and engineers who are now receding to the distant edges of our collective memories should be elevated accordingly.

Beyond this homage to our technology forebears, is there anything else we can learn by looking back into the hazy past? We can certainly remind ourselves to be cautious about predicting the future of technology, lest we find ourselves drawing conclusions prematurely that we might later come to regret:

"... it would be no more correct to state that the rectifier can be used to replace the commutator than it would be to state that a gasoline engine can be used to replace the horse. Both gasoline engine and horse may be used as a source of power for locomotion, but certainly no one would expect to hitch a gasoline engine to the shaft of a wagon for the purpose of pulling it" [38].

We can also learn lessons regarding the need for patience and perseverance in our never-ending quest to introduce new technology. The frustration experienced by our technology forebears in their largely unsuccessful efforts to bring their early electronic ac drives into wide industrial usage is almost palpable in the written records. Unfortunately, good ideas often take a long time to reduce to practice, sometimes requiring many years before subsequent technical breakthroughs finally vindicate the value of the original ideas.

Just as past generations of electronic drive engineers from the first half of the century found that their triggered-arc switches were too expensive and unreliable, today we struggle against these same old enemies on new fronts. So we end with the same question that our technology forebears must have repeatedly asked themselves as they searched for new solutions: What comes *next*?

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