Barry C. Brusso

Celebrating the Life and Legacy of Dr. Thomas A. Lipo

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A giant in our field has left us. Dr. Thomas A. Lipo passed away in his home in Middleton, Wisconsin, on 8 May 2020 after a two-year battle with cancer. Given the tremendous impact that he had on both the technology in our field and on the personal lives of so many in our international professional community, it is difficult to overstate the sense of shock and sadness that was experienced by so many of those who knew him personally or by reputation. However, Dr. Lipo led a rich life that deserves to be remembered and celebrated by all of us who are working in this field.

Who was Dr. Lipo? It is hard to find all of the right words to describe him since he influenced our lives in so many ways and roles: innovator, inventor, pioneer, author, editor, theorist, analyst, researcher, educator, mentor, leader, and informal ambassador—all of these and more.

The purpose of this article is to pay tribute to Dr. Lipo's life, his accomplishments, and the rich legacy of technical contributions that his life work has bequeathed to all of us in our field. In addition to simply highlighting his accomplishments, this article provides a welcome opportunity to remind ourselves about who Dr. Lipo was as a person, the life path that he followed, and how his life can serve as an inspiration for all of us who follow in his path.

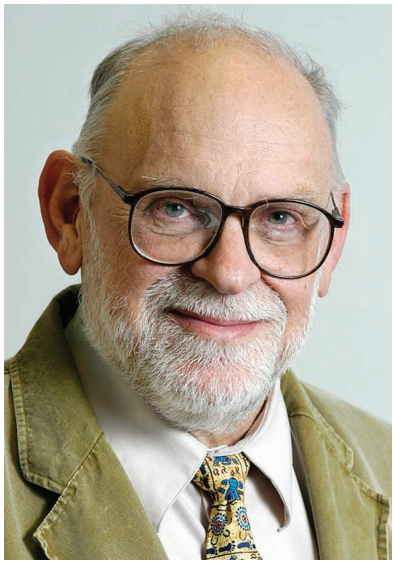

FIGURE 1. Dr. Thomas A. Lipo (1938–2020). (Source: WEMPEC, UW-Madison; used with permission.)

The Early Years

Thomas A. Lipo (Figure 1) was a native son of Milwaukee, Wisconsin, where he was born (3 February 1938) and raised. During his youth, Dr. Lipo was a victim of poliomyelitis, like too many other young people in the United States at the time. He recovered, but the virus left him with permanent damage to his leg muscles, which degraded his mobility throughout the rest of his life. However, this setback did not prevent him from aggressively pursuing a career in engineering.

Dr. Lipo earned his bachelor's and master's degrees in electrical engineering at Marquette University in Milwaukee, Wisconsin. He worked in training programs at Allis-Chalmers Manufacturing Company in Milwaukee during both his undergraduate and master's programs, which helped him to develop his nascent interest in electrical power equipment and electric machines, in particular. The title of his master's thesis was "Analysis of Single-Stator Double-Rotor AC Machine," foreshadowing his lifelong passion for innovative machine topologies. It was during this period that Dr. Lipo began mastering the skills of using analog computers to carry out machine analyses and simulations, providing a solid foundation that served him well during the coming years.

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For his Ph.D. studies, Dr. Lipo enrolled at the University of Wisconsin-Madison (UW-Madison) in 1966. His doctoral research program was supervised by Prof. Paul C. Krause, who was then a young professor in the early stages of his academic career. The title of Dr. Lipo's Ph.D. thesis was "Lyapunov Stability Analysis of a Class of Inverter Drives," a control-oriented research topic that reflected the breadth of his engineering skills and technical interests that would become hallmarks of his professional career. One of the members of his Ph.D. committee was another young UW-Madison professor, Dr. Donald Novotny, who would play a pivotal role in Dr. Lipo's career path a little more than 10 years later.

In August 1968, Dr. Lipo received an NRC Research Fellowship from the National Research Council for work at the University of Manchester Institute of Science and Technology in Manchester, England. While there, he established personal contacts with many European technologists, many of which he cultivated during the rest of his career. They gave him insight into European developments as well as his first experience with international travel, for which he developed a deep affinity during his academic career.

The GE Years

In August 1969, Dr. Lipo began his employment at General Electric Corporate Research and Development (GE-CRD) in Schenectady, New York. The ten years that Dr. Lipo worked at GE were highly productive for him in terms of the research he conducted and the technical papers that he published as a young engineer. During this time, he became highly proficient in using the best computational machines that were available at the time, including, in chronological order, analog, hybrid (analog/digital), and digital computers. Figure 2 captures Dr. Lipo during his early years at GE with an analog computer behind him. He is accompanied by Burnice ("Bernie") Bedford, a coauthor with Dr. Richard G. Hoft of *Principles of Inverter Circuits*, one of the first hard-cover books focused on thyristor-based inverter technology.

Dr. Lipo used these computational tools to conduct research and publish technical papers that analyzed the dynamic behavior of thyristor-based inverters and rectifiers in combination with induction and synchronous machines [1] [Figure 3(a)]. While much of his work involved time-domain simulations, he also made valuable contributions to the frequency-domain analysis of machines, one of which [2] resulted in his first of more than 26 prize paper awards in 1974 [Figure 3(b)]. As time went on, Dr. Lipo also began collaborating more frequently with his GE colleagues to apply these powerful analytical tools to synthesize innovative thyristor-based ac drive technology, such as the new starting technique for load-commutated synchronous machine drives reported in [3] [Figure 3(c)]. Dr. Lipo appears with several of his GE colleagues in Figure 4 later during the 1970s with a hybrid computer in the background.

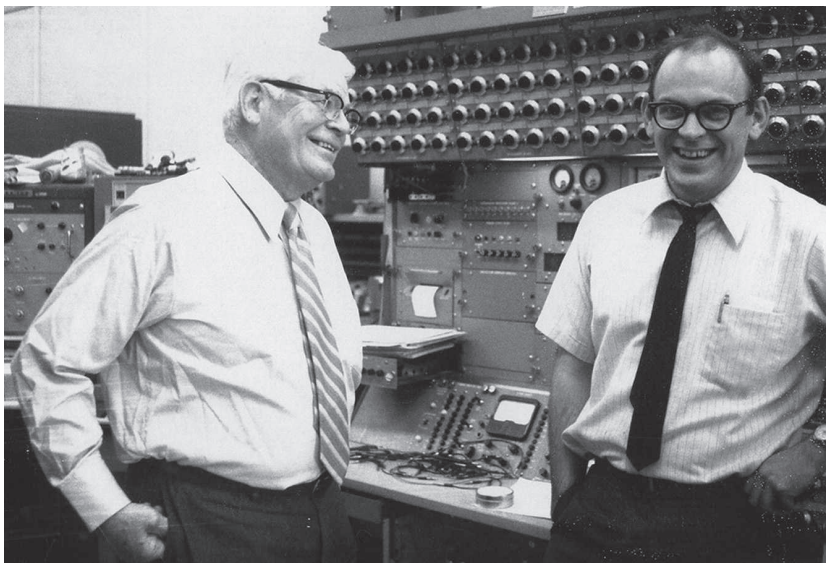
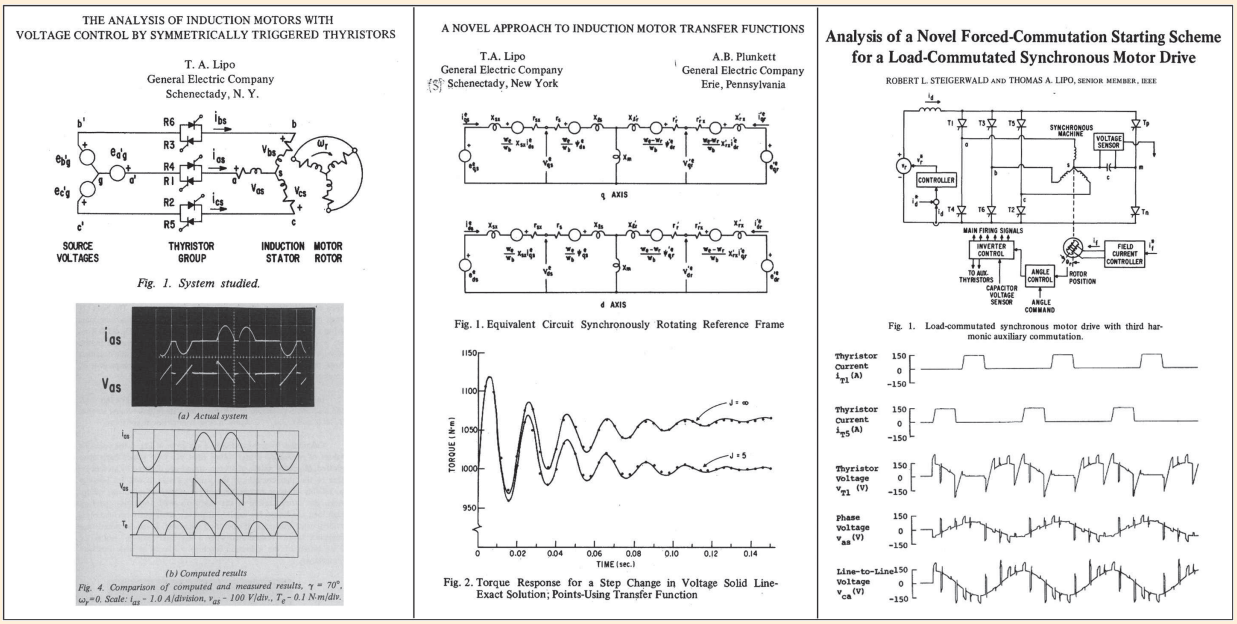


FIGURE 2. Dr. Lipo (right) with early power electronics pioneer Burnice Bedford in the GE-CRD laboratory with an analog computer in the early 1970s. (Source: Museum of Innovation and Science; used with permission.)

The Wisconsin Electric Machines and Power Electronics Consortium Years

Dr. Lipo maintained a close relationship with his Ph.D. thesis supervisor, Dr. Paul Krause, who had moved from UW-Madison to Purdue University in the early 1970s. They coauthored several papers, and Dr. Lipo spent a research sabbatical year at Purdue during 1973–1974 as a visiting associate professor. This sabbatical year set the stage for Dr. Lipo to permanently enter academia five years later, when he joined the electrical engineering faculty at Purdue as a tenured professor in 1979. However, he was lured away to UW-Madison two years later by Prof. Donald Novotny, who was in the process of launching the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC) in 1981. This concept of a university-industry partnership was rather new and untested at that time, combining the pursuit of long-term technology advances in the fields of electric machines, power electronics, and motor drives with the goal of educating students to become future engineering leaders in these fields. The collaboration of Dr. Novotny and Dr. Lipo (Figure 5) proved to be a potent and effective partnership that was critical to WEMPEC's transition from a speculative proposal into a highly successful academic



(a) (b) (c)

FIGURE 3. Examples of early Lipo articles during the GE years (1970s) addressing the stability and dynamic performance of ac machines with thyristor-based inverters: (a) induction motor thyristor voltage control (1971) [1], (b) induction motor transfer functions (1974) [2], and (c) the starting scheme for load commutated synchronous motor drive (1979) [3].

program that continues to thrive today celebrating its 40th anniversary in 2021.

The move from industry to academia gave Dr. Lipo the intellectual stimulation he craved to expand his vision for the future of electric machines and drives in several directions simultaneously, including innovations in power electronics, electric machines, and control. The highly eclectic and wide-ranging technical interests that he persistently pursued over the next 40 years of his professional career were hallmarks that highlighted the strengths of both his intellect and curiosity. He was determined to focus his energies on creating and exploring his new ideas with his graduate students until the end of his life.

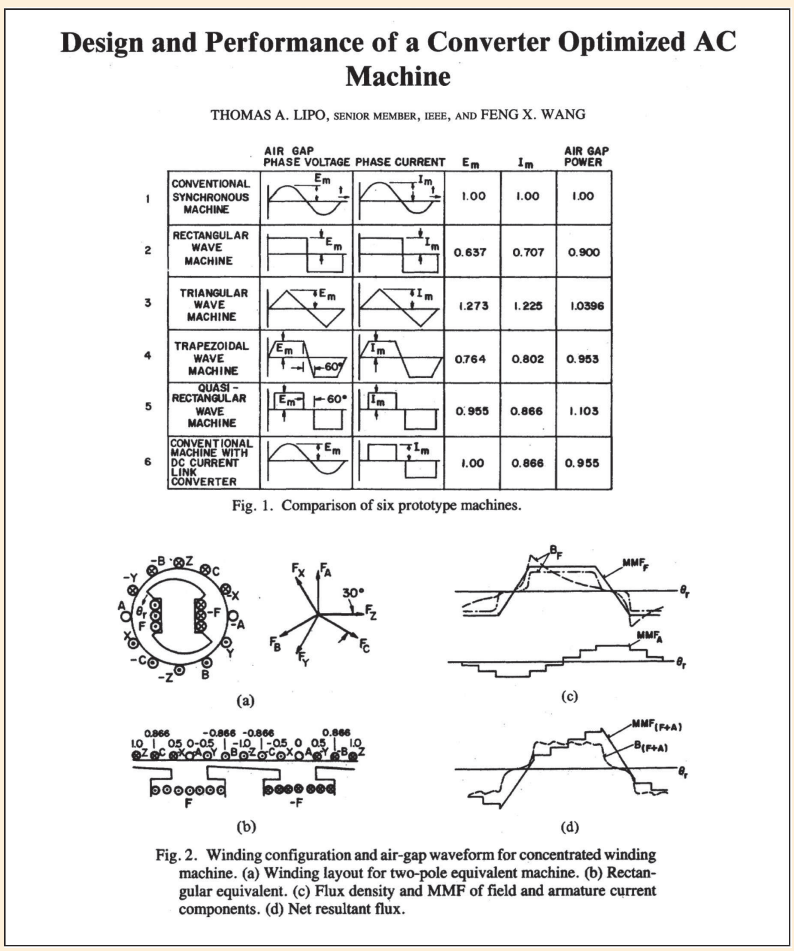
A good example of Dr. Lipo's approach to new technology during his early years at UW-Madison is his pursuit of the concept of converter-optimized ac machines, documented in a 1982 article [4] that earned him the third of his prize paper awards (Figure 6). Although this machine was never commercialized in the form that

FIGURE 4. Dr. Lipo (left, standing) with GE engineering colleagues (left to right) Paul Espelage, William G. Wright, and Loren Walker in the late 1970s working on simulations of a current-source inverter drive with a hybrid computer in the background. (Source: Museum of Innovation and Science; used with permission.)

he envisioned at the time, several of the underlying concepts that were proposed to optimize the machine design for inverter excitation foreshadowed later motor drive developments that were highly successful. For example, the concept that Dr. Lipo was proposing—to purposely abandon sinusoidally distributed windings for square-wave spatial distributions of air-gap magnetic flux density—is critical to the highly successful brushless dc permanent magnet (PM) synchronous machines using concentrated windings that were just beginning to appear in the marketplace when this article was written.

(a) (b)

FIGURE 5. The WEMPEC co-founders Dr. Lipo and Dr. Don Novotny (a) working with students in the WEMPEC lab during early 1980s and (b) commemorating WEMPEC's 35th anniversary in 2016 (Dr. Lipo, right). (Source: WEMPEC, UW-Madison; used with permission.)



Design and Performance of a Converter Optimized AC Machine

THOMAS A. LIPO, SENIOR MEMBER, IEEE, AND FENG X. WANG

		AIR GAP PHASE VOLTAGE	PHASE CURRENT	E_m	I_m	AIR GAP POWER
1	CONVENTIONAL SYNCHRONOUS MACHINE	E_m	I_m	1.00	1.00	1.00
2	RECTANGULAR WAVE MACHINE	E_m	I_m	0.637	0.707	0.900
3	TRIANGULAR WAVE MACHINE	E_m	I_m	1.273	1.225	1.0396
4	TRAPEZOIDAL WAVE MACHINE	E_m 60°	I_m	0.764	0.802	0.953
5	QUASI-RECTANGULAR WAVE MACHINE	E_m 60°	I_m	0.955	0.866	1.103
6	CONVENTIONAL MACHINE WITH DC CURRENT LINK CONVERTER	E_m	I_m	1.00	0.866	0.955

Fig. 1. Comparison of six prototype machines.

(a) (c) (b) (d)

Fig. 2. Winding configuration and air-gap waveform for concentrated winding machine. (a) Winding layout for two-pole equivalent machine. (b) Rectangular equivalent. (c) Flux density and MMF of field and armature current components. (d) Net resultant flux.

FIGURE 6. An early article (1984) written by Dr. Lipo on converter-optimized ac machine design after he joined WEMPEC [4].

Dr. Lipo was unabashed about taking new concepts for advanced motors and power converters wherever he could find them and then adding his own ideas to leave his personal mark on those technologies. A good example of this is the contributions he made in the area of resonant power conversion for high-power applications. Following the arrival of Dr. Deepak Divan, who joined the UW-Madison WEMPEC faculty in the mid-1980s and attracted worldwide attention for his groundbreaking work on resonant dc link inverters, Dr. Lipo attracted attention for his innovative contributions to the development of resonant ac link inverters for both power system [5] and motor drive [6] applications (Figure 7). As illustrated in the figure, this approach used back-to-back full-bridge inverters connected by an *LC*-based resonant ac link that required bidirectional controlled switches in the inverters. Both of these cited articles earned prize paper awards for Dr. Lipo and his coauthors, which included a young Dr. Seung-Ki Sul, who was visiting WEMPEC during this time.

Another very notable technical contribution came later in the 1980s in a article that had far-reaching consequences for brightening the future of PM synchronous machines in traction drive applications. More specifically, the 1988 article [7] written by Dr. Lipo and Dr. Schiferl examined the power capability of PM synchronous motors in drive applications, revealing that the constant-power speed range of these machines can be extended to theoretically infinite speeds, but only if the machine is specifically designed with this objective in mind (Figure 8). This article, combined with other parallel developments

in high-performance interior PM (IPM) synchronous machine drives and then-new insulated-gate bipolar transistor-based inverters, set the stage for the dominant position that IPM machines currently hold in the traction drives of commercially manufactured passenger hybrid- and battery-electric vehicles.

In addition to his long-standing interest in advanced PM machine-drive technology, Dr. Lipo also demonstrated an unshakable fascination and devotion to synchronous-reluctance machines and their drives. The articles that he published about this machine-drive technology span more than 50 years, beginning in 1967 with an analysis of the machine's stability characteristics [8] [Figure 9(a)] and extending to one of the last articles published before the end of his life on a concept for a new hybrid synchronous-reluctance machine mated with a surface PM rotor sharing the same rotor shaft [9] [Figure 9(b)]. Midway during this 50-year period, he coauthored an article with his then-student Dr. Longya Xu and colleague Don Novotny in 1991 on vector control techniques for synchronous-reluctance machines that earned him his 11th prize paper award [Figure 9(c)].

Dr. Lipo and his students also made pioneering contributions to the early development of several concepts for doubly salient ac machines that used either PMs or auxiliary field windings to enhance their torque production. Two prize-winning examples of these articles that highlight his contributions include a 1992 article that uses stator-mounted magnets to supplement the magnetic flux linkage produced by the stator windings [10] [Figure 10(a)] and a 1994 article that foregoes magnets in favor of auxiliary windings in the stator slots that improve the switching (commutation) of the flux from phase to phase to enhance the machine's performance [11] [Figure 10(b)]. It is worth noting that these articles and others contributed by Dr. Lipo and his students laid the foundation for a major surge in international interest in switched-flux PM machines during recent years, which has been spearheaded by Prof. Z.Q. Zhu at the University of Sheffield.

The space available in this article makes it impossible to do justice to all of the other technical areas within our field where Dr. Lipo and his students made notable contributions. A partial and woefully incomplete list of these includes

- the analysis and suppression of inverter-induced shaft voltages and bearing currents
- open-winding machine drive configurations
- inverter common-mode electromagnetic interference reduction

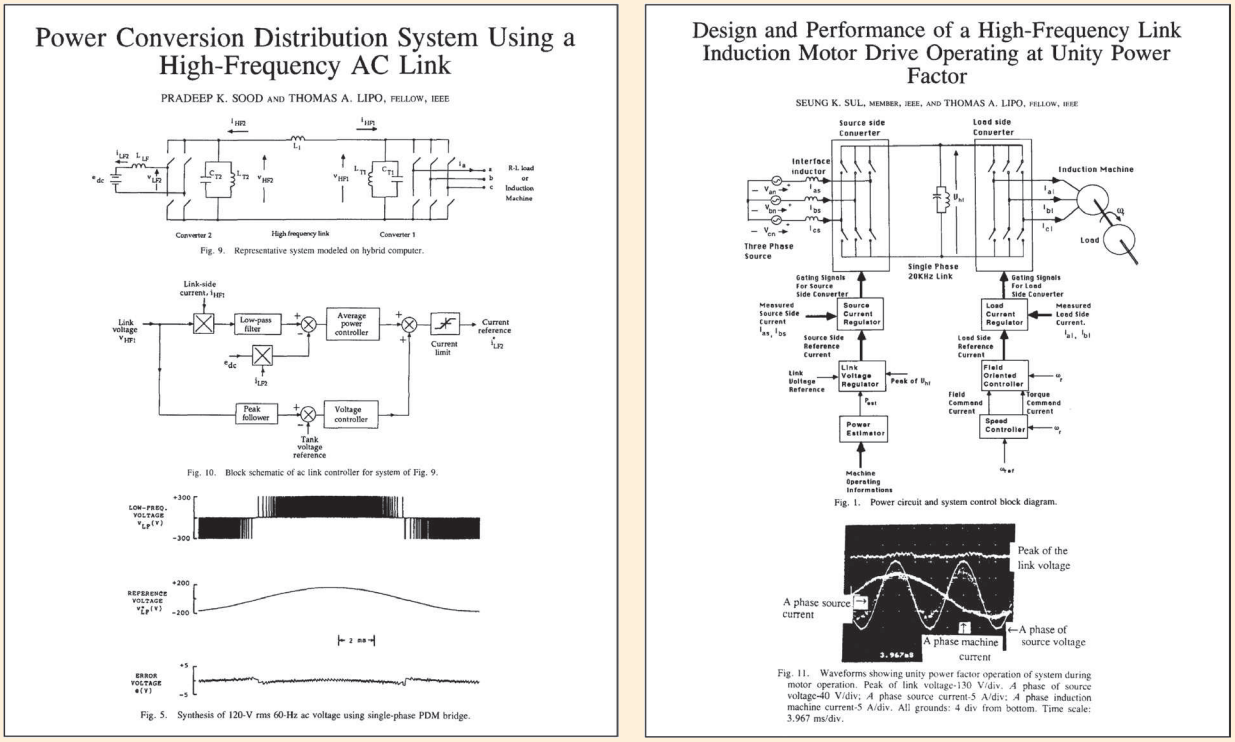
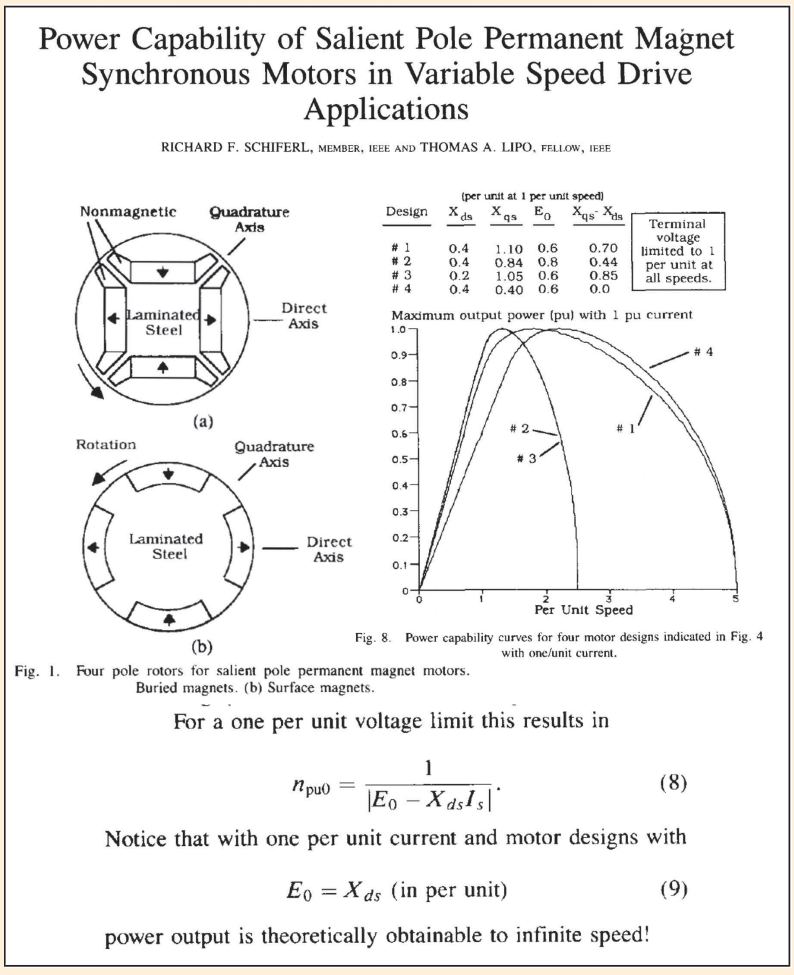


FIGURE 7. Two Lipo articles addressing high-frequency ac link power converter applied to (a) a power system (1988) [5] and (b) an induction motor drive (1990) [6].



Power Capability of Salient Pole Permanent Magnet Synchronous Motors in Variable Speed Drive Applications

RICHARD F. SCHIFERL, MEMBER, IEEE AND THOMAS A. LIPO, FELLOW, IEEE

Fig. 1. Four pole rotors for salient pole permanent magnet motors. Buried magnets. (b) Surface magnets.

(per unit at 1 per unit speed)

Design	X_{ds}	X_{qs}	E_0	X_{qs} - X_{ds}
# 1	0.4	1.10	0.6	0.70
# 2	0.4	0.84	0.8	0.44
# 3	0.2	1.05	0.6	0.85
# 4	0.4	0.40	0.6	0.0

Terminal voltage limited to 1 per unit at all speeds.

Fig. 8. Power capability curves for four motor designs indicated in Fig. 4 with one/unit current.

For a one per unit voltage limit this results in

$$n_{pu0} = \frac{1}{|E_0 - X_{ds} I_s|}. \quad (8)$$

Notice that with one per unit current and motor designs with

$$E_0 = X_{ds} \text{ (in per unit)} \quad (9)$$

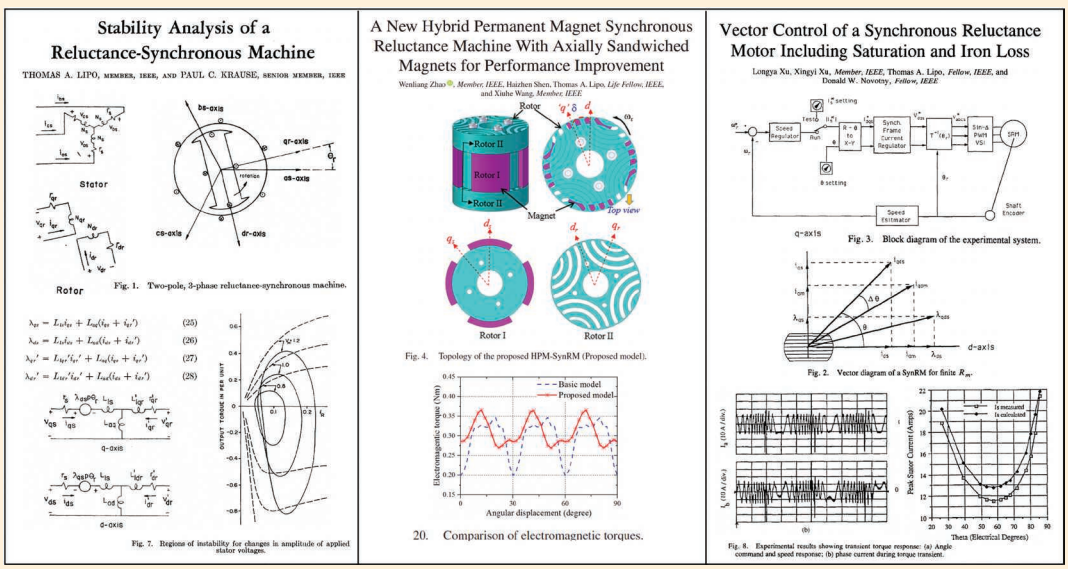
power output is theoretically obtainable to infinite speed!

FIGURE 8. A 1988 Lipo article identifying the PM machine design requirement for the optimum flux weakening speed range [7].

- using specialized pulsewidth modulation strategies
- brushless excitation of synchronous machines using airgap spatial harmonic fields
- vernier PM machines
- hybrid multi-level power converters
- rotor parameter identification and adaptive controllers for field-oriented induction machine drives
- flux sensors and position sensor elimination algorithms for high-performance ac drives
- fault analysis and fault-tolerant topologies for PM machines and drives
- and many more.

Major Professional Metrics and Awards

Given the breadth and depth of the technical contributions summarized in the preceding section, it is not surprising that Dr. Lipo amassed an awe-inspiring set of professional metrics during his career. Table 1 provides a summary of the most notable of these uniformly impressive totals. Although these metrics speak for themselves, a few deserve some additional comments.



Stability Analysis of a Reluctance-Synchronous Machine

THOMAS A. LIPO, MEMBER, IEEE, AND PAUL C. KRAUSE, SENIOR MEMBER, IEEE

Fig. 1. Two-pole, 3-phase reluctance-synchronous machine.

Fig. 7. Regions of instability for changes in amplitude of applied stator voltages.

(a)

A New Hybrid Permanent Magnet Synchronous Reluctance Machine With Axially Sandwiched Magnets for Performance Improvement

Wenliang Zhao, *Member, IEEE*, Huizhen Shen, Thomas A. Lipo, *Life Fellow, IEEE*, and Xiuhe Wang, *Member, IEEE*

Fig. 4. Topology of the proposed HPM-SynRM (Proposed model).

20. Comparison of electromagnetic torques.

(b)

Vector Control of a Synchronous Reluctance Motor Including Saturation and Iron Loss

Longya Xu, Xingyi Xu, *Member, IEEE*, Thomas A. Lipo, *Fellow, IEEE*, and Donald W. Novotny, *Fellow, IEEE*

Fig. 3. Block diagram of the experimental system.

Fig. 2. Vector diagram of a SynRM for finite R_m.

Fig. 8. Experimental results showing transient torque response: (a) Angle command and speed response; (b) phase current during torque transient.

(c)

FIGURE 9. Three Lipo articles spanning nearly 50 years on synchronous reluctance machine topics: (a) stability (1967) [8], (b) machine topology (2018) [9], and (c) vector control (1991) [10].

For example, the number of books and book chapters written by Dr. Lipo do not do justice to the impact that these publications continue to have on both students and professionals working in the field. The majority of the books evolved from course notes that Dr. Lipo developed and continually improved upon during the process of teaching graduate courses on electric machines and drives for nearly 30 years at UW-Madison. While a couple of these books have relatively limited circulations among UW-Madison students, the majority of them are available from major publishers (including Wiley/IEEE Press) and enjoy large circulations and iconic reputations among the international community. In particular, *Introduction to AC Machine Design* and *Pulse Width Modulation for Power Converters* (coauthored with Dr. Grahame Holmes) are must-have reference books for professional machine designers and inverter control specialists, respectively, around the world.

Similarly, the raw number of 120 Ph.D. and M.S. students that

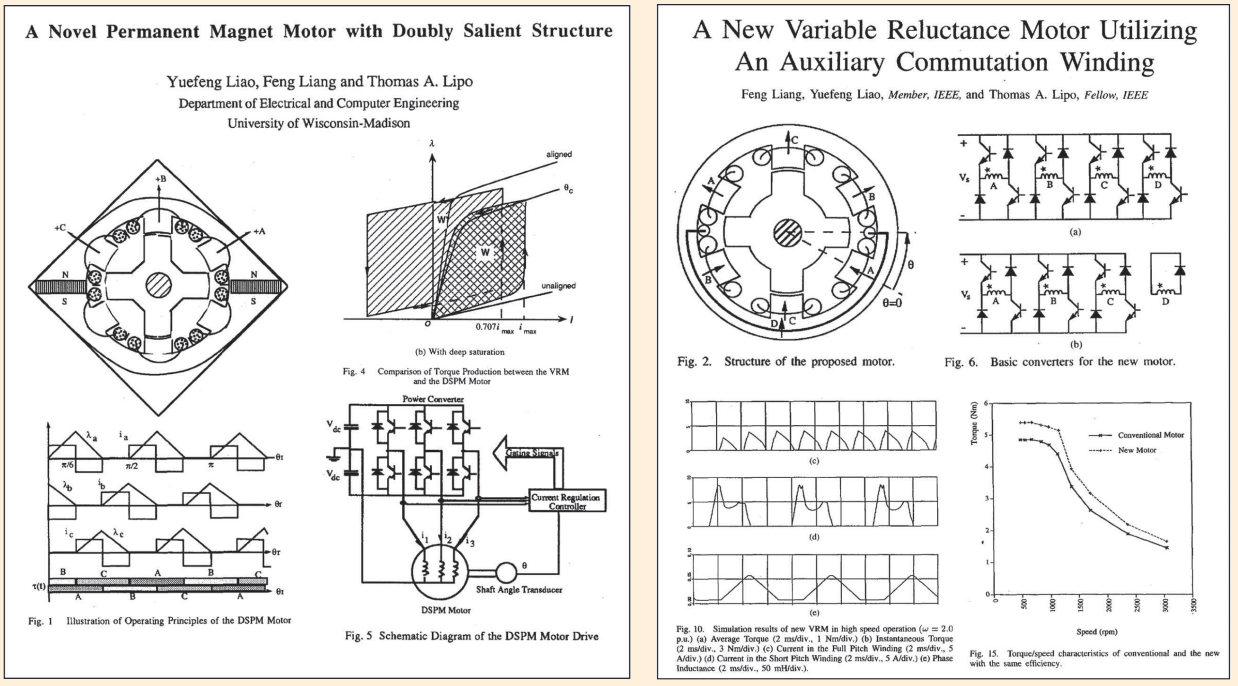


FIGURE 10. Two of several Lipo articles focused on doubly salient reluctance machines combined with (a) permanent magnets (1992) [11] and (b) commutation assistance windings (1994) [12].

FIGURE 11. A banquet in Wuhan, China, (Oct. 2013) honoring Dr. Lipo (seated at table, center) that was organized by his many former graduate students and other special friends in China. Dr. Lipo's wife Sandra Eimen is seated next to him. (Source: Dr. Ronghai Qu, HUST; used with permission.)

Table 1. Summary of T.A. Lipo's key professional metrics

- >700 archival Transactions and conference articles
- >50,000 citations in the global technical literature
- >25 prize paper awards
- >50 patent awards and applications
- Five books and eight book chapter section contributions
- >120 Ph.D. and M.S. students graduated
- Seven visiting professorships/fellow/research professor appointments at international universities

Table 2. T.A. Lipo's major professional awards and recognitions

- Elected, U.S. National Academy of Engineering, 2008
- Fellow, Royal Academy of Engineering (Great Britain), 2002
- Fellow, National Academy of Inventors (United States), 2013
- IEEE Medal in Power Engineering, 2014
- Hilldale Award in Physical Sciences, University of Wisconsin-Madison, 2004
- IEEE Nikola Tesla Technical Field Award, 1995
- William E. Newell Award, the IEEE Power Electronics Society, 1990
- Outstanding Achievement Award, the IEEE Industry Applications Society, 1986
- Fulbright Fellow, 2008
- IEEE Fellow, 1987

graduated under Dr. Lipo's supervision does not adequately convey the important roles that many of his graduates are now playing in our field around the world. A significant number of his Ph.D. graduates entered academia themselves, and several of them have become highly renowned during their careers at universities around the world.

Another key insight missing from the student numbers is the special role that Dr. Lipo played in welcoming international students wishing to pursue graduate studies with him at UW-Madison, well before it became fashionable to do so at U.S. universities. Most notably, Dr. Lipo was one of the earliest U.S. faculty members in our field to welcome students from China after China–U.S. relations improved in the 1980s. It is important to recall that many around the world of these earliest graduate student candidates were missing the typical academic credentials for admission that we expect today because of the conditions that existed in China before doors began to open. However, Dr. Lipo quickly began to welcome Chinese students to Madison, and his openness was rewarded with a number of world-class students who played key roles in many of the technical accomplishments discussed in this article (Figure 11). Dr. Lipo was always predisposed to say "yes" when approached by prospective students from around the world who needed invitations and, in many cases, funding to be able to pursue their dream of coming to the United States to become one of his students. This was equally true for short-term visiting professors and scholars coming from every corner of the globe.

Dr. Lipo was an avid international traveler for much of his career at UW-Madison. His extended absences from Madison were noted by his students, who became convinced that the first two initials in his name stood for "Trans-Atlantic." Nevertheless, Dr. Lipo was a very effective informal ambassador for WEMPEC in the international community of experts in our field. As noted in Table 1, he was highly sought after by many international universities as a visiting guest professor who energetically engaged with both faculty members and students during his extended trips abroad.

FIGURE 12. The 2002 induction ceremony inducting Dr. Lipo (left) into the Royal Academy of Engineering (Great Britain). Prince Philip, senior fellow of the Academy, is fourth from the left. (© Royal Academy of Engineering; used with permission.)

Major Awards

Table 2 provides a summary of the major national and international awards that Dr. Lipo received during his professional career in recognition of his exemplary technical accomplishments in our field. The list includes the IEEE Medal in Power Engineering, the highest IEEE award for professionals in our field. Figure 12 provides a view of the induction ceremony in 2002, where he accepted the title of Fellow of the Royal Academy of Engineering in Great Britain, with Prince Philip in attendance.

IEEE Service

Dr. Lipo was an active member of the IEEE Industry Applications Society throughout his professional career. He held many leadership positions in the Society, beginning with chair of the Industrial Drives Committee in 1986–1987, leading to his service as chair of the Industrial Power Conversion Systems Department, and culminating with Society president in 1994. Dr. Lipo also held some important leadership positions in the then-new IEEE Power Electronics Society, including service as a member of their Administrative Committee and founding editor of *IEEE Transactions on Power Electronics*.

Family and Leisure

In view of everything that Dr. Lipo accomplished during his professional career, it is difficult to imagine how he found time to do anything else. Despite the burdens of his professional activities, Dr. Lipo and his wife Christine (Chris) raised four children over the period that spanned the years when he was living in Schenectady and Madison. Those children grew up and raised families of their own, making him a grandfather with nine grandchildren at the time of his passing. During any time that Dr. Lipo was not occupied by his professional work or family, he focused on his passions of folk music, fine food, world travel, and fishing (Figure 13).

In Closing

Dr. Lipo led a rich professional life that spanned the boundary between industry and academia as well as many international boundaries in a uniquely productive way that touched the lives of thousands of students, engineers, and faculty colleagues around the world. His impressive record of technical accomplishments represents a remarkable legacy that will live on, influencing the professional careers of power engineers in our field for many generations to come. Rather than mourning his passing, it is much more appropriate for us to be celebrating his singularly successful career and our collective good fortune for having him as a professional colleague for more than 50 years. May we gain inspiration from the remarkable life he led marked by his insatiable curiosity and irrepressible creativity. Rest in peace.

FIGURE 13. The evidence of another successful offshoot of Dr. Lipo's long-term partnership with Dr. Novotny. (Source: Dr. Donald Novotny, UW-Madison; used with permission.)

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