International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 4, April - 2014

A Brief History of Power Electronics and Drives

Eldho Joy
M-Tech student, Dept. Of EEE.
Rajagiri School of Engineering and Technology
Kerala,India

Unnikrishnan L
Assistant Professor, Dept. Of EEE.
Rajagiri School of Engineering and Technology
Kerala,India

***Abstract*—Speed control of electric motors in industrial sector is advancing day by day. The use of power electronic devices in motor drives creates efficient speed control with reduced cost. This paper reviewed the advancement in industrial drives and control from its beginning to the modern drive technology. The paper deals with power semi conductor devices, converter circuits, motor drives and various speed control techniques in the order of their advancement.**

***Index Terms*—Rectifier, Thyristor ,Insulated gate bipolar transistor, Vector control, Space vector modulation, Field programmable gate array.**

I. INTRODUCTION

Since the invention of the motor which converts electrical energy into mechanical energy, in the second half of 19th century it has been used in domestic as well as industrial applications.The advancement in science lead to the drive technology in order to match the speed of motors to the optimum operating point of a driven machine or application.

The electric motor has been used throughout the whole of the 20th century and the application of motion technology also developed.The motor and its control gear have developed considerably in recent years as power electronics improve with the progress of semiconductor technology. It has resulted in the improved operating convenience of many machines from heavy and large industrial equipment such as rolling mills in steel making plants, and paper making machines in paper mills. The most advanced motor drive technology, such as the latest power electronics and vector control, is applied to these products, and it has become widely used in all such fields. On the other hand, the electric power used by electric mechanical energy conversion which motors achieve, is the largest world wide sector for energy consumption accounting for about 70% of the total industrial electric power produced. As a result, they were responsible for many of the problems since the end of the last century where the influence of human beings affecting the earth's environment can not now be disregarded. the global warming phenomenon due to carbon dioxide emissions, etc. Moreover, power electronics is deeply involved in the development of new alternative energy sources such as photo-voltaic cells powered by the sun, fuel cells, and wind power generation progresses. The improvement of motor drive technology and power electronics as its core becomes a key to solve the many problems facing the earth's environment in the future, and it has the potential to considerably contribute to environmental preservation.

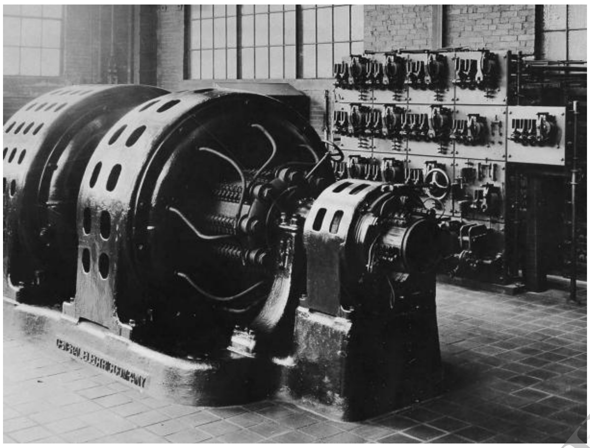
II. MOTOR CONTROL TRENDS

A. Era of rectifiers

The speed control technique originated by the introduction of a three-phase induction motor with a polyphase slip-ring rotor into which resistors connected for starting and control.This is done by Dobrowlsky in 1890. Speed control techniques are advanced by the method of Ward Leonard Control, also known as the Ward Leonard Drive System introduced by Harry Ward Leonard , used in DC motor speed control system in 1891[1][2]. The system he proposed was based upon the inherently variable speed DC machine which is controlled by armature resistors.This system works with three machines ,A three phase ac motor,a dc generator and a dc motor. His work was not universally accepted at the time and attracted much criticism, understandably, as it required three machines of similar rating to do the job of one.The system provides smooth speed control from maximum to minimum speed. Then in 1901,Peter Cooper Hewitt came with mercury-arc discharge principles for the explicit purposes of electrical rectification in [2]. in 1902 P. H. Thomas came with an idea of phase angle control[2]. In 1904,Fleming invented thermionic diode for rectification purpose[3]. In 1905 Steinmetz invented high voltage rectifier for street lightning[4].The triode valve was patented by Lee De Forest in 1907 and was called the Audion. It was initially used as a radio detector. The triode valve is a switch device and an amplifier of electrical signals.It was an important element in radio,television,radar and computer systems before the development of transistors[5]. In 1912, E.F.W. Alexanderson of the General Electric Company introduced Magnetic amplifier for radio telephony.It is a method for modulating the current fiom a high-frequency alternator so that it could be used for radio telephony [6]. With 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 themionic triode vacuum tube in the early 1900s, attempts were made to apply these principles to power control applications.

A competing method for the efficient speed control of large slip-ring induction motors was known as the Kramer system, announced in Germany in 1906.These systems came to be marketed primarily by the Westinghouse Electric Company, but a few Kramer drives were built by General Electric as well early in the twentieth century.

A major alternative to the Kramer system for wound-rotor induction machine drives was the Scherbius system, introduced in Germany in 1907.Historical evidence indicates that pioneering Scherbius rolling mill drives were installed at the Saucon works of the Bethlehem Steel plant around the time of World War I. The Scherbius system was first marketed by the General Electric Company in about 1916. This development resulted from a licensing agreement between GE and the system's inventor, Arthur
Scherbius of Zurich, Switzerland[7],[8].



Fig,1:The Scherbius regulating M-G set that was a part of the 2,000-HP, 65/100 rev/min, 6,600-V induction motor drive in a structural mill at the Saucon Works.

The most successful of these integrated configurations was the Schrage motor ,another German development that was first introduced in 1914. Schrage introduced a system based upon an induction motor with a commutator on the rotor. This machine proved to be very popular, requiring no auxiliary machines and was very reliable. It found large markets, particularly in the textile industry and some other niche applications. This made possible the direct control of voltage applied to the armature of a d.c. machine so as to apply Ward–Leonard control without additional machines.In 1930 ,the ideas of inversion which converts d.c to variable voltage or variable frequency ac had been established.In 1931, Direct a.c. to a.c. conversion by means of cycloconverters was introduced for railway service. The Nyquist stability criterion was developed in 1932 [9] and in 1938,the Bode stability criterion developed.The first variable frequency ac drive which is the thyratron cycloconverter drive of a synchronous machine was installed in the Logan Power Station in 1934. Although thyratron power ratings gradually increased during the 1930s, they never caught up with the ratings of their pool cathode counter parts.. The ignitron was developed by Joseph Slepian and L. R. Ludwig, at Westinghouse in 1933 [10]. It is a form of poolcathode 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 Thyratrons and ignitrons were the first high-power controlled rectifiers which were available for use in electronic power converters. The electronic Kramer drive system introduced by Alexanderson[11]. In 1938 that replaces the electromechanical rotary converter in the classic Kramer system with a static uncontrolled rectifier using power tubes. A year later in 1939, Stohr in Germany discussed electronic counterparts to the classic Scherbius system. The transistor was invented by John Bardeen, Walter Brattain and William Shockley at Bell Labs in December, 1947. Announced to the public in June, 1948.The major drawbacks of vacuum tubes are overcomed by transistors which had a longer lifetime,less weight,rugged and no need of filament current. The commercial use of transistors increased in the 1950's, beginning with telephone switching equipment and military computers in 1952, hearing aids in 1953, and portable radios in 1954.[12]

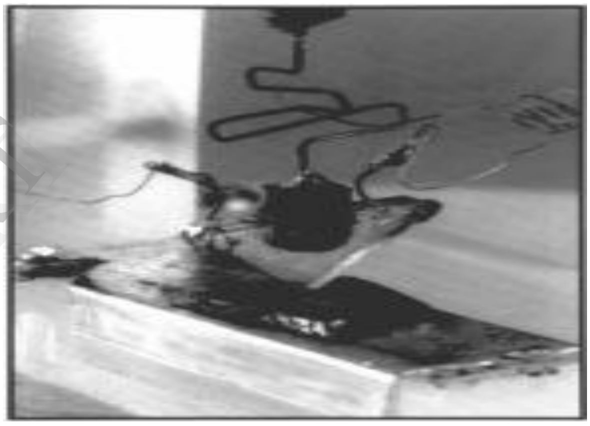


Fig 2.First transistor

B.Era of Thyristors-First generation power devices.

Power semiconductor devices constitute the heart of modern power electronic apparatus.The power electronics era began with the invention
of the glass bulb mercury arc rectifier at the beginning of this century. However, the modem solid-state power electronics era started in the last 1950's with the invention of thyristors, which are also known as silicon-controlled rectifiers. The advent of the thyristor revolutionizes power electronics, bringing power electronics to the marketplace on a large scale. In 1957,the thyristor [silicon-controlled rectifier
(SCR)] was introduced by General Electric[13]. Also in 1957 ,the 'back to back' reversing d.c. drive introduced. The improvement in their ratings brought a tremendous use of THY (static)-Ward Leonard DC drives instead of motor-generator(M-G) sets. In the middle of 1960s. the first application of static Ward Leonard DC drives began for rolling mills in the USA ,their application was followed by many other industrial countries since the late 1960s. The application of thyristors lead to dramatic improvements in

drive performance, power loss and equipment size reduction. Rapid Spread of Thyristor dc Drive to Large- Capacity Mill Drive in the Metal Industry from the Mid-1960s.Commercialization of Voltage and Current Source Thyristor Inverter drives are came into industries in mid 1960's to feed large numbers of induction motors or reluctance motors, In 1963 Gain–bandwidth relationships of power converters were investigated[14].In the mid of 1960's Pulse Width Modulation techniques are emerged for the inverter control. The earliest PWM technique was the sine triangle method which is proposed by Schonung & Stemmler in 1964.In this method,the switching instants of the inverter legs are decided by the points of intersection of a high frequency (anywhere from 450 hertz to a few kilohertz) triangular wave in the range of 450 hertz to several kHz,and a sinewave at the frequency of the required fundamental motor voltage. The triangle is referred to as the carrier and the sine as the reference.

In 1964,Principles of Inverter Circuits was published and at that time,almost all ac drive main circuit topologies using thyristors were introduced.The first high-speed railway which is Shinkansen using dc drive of diode rectifiers began operation in Japan in 1964[16]. In the same year,the electric vehicle "Electrovair1" using an IM drive of thyristor inverter with silver-zinc battery was introduced by GM.The development of simple and efficient methods of obtaining forced-commutation was the main problem in the thyristor inverter, and many circuits were proposed world wide[17]. Among them, the CT feedback circuit,that can permit the return of the trapped energy to the DC supply with current transformers was invented by E. Ohno and M. Akamatsu in 1964[13]. With the invention of forced commutation circuits for SCRs, chopper driven DC drives became popular. The armature current control in such drives is achieved by duty cycle modulation of a fixed DC bus voltage. For traction applications which required four quadrant operation over a wide speed range, both the armature and the field current were regulated using the DC-DC choppers. Since the switching frequency of the forced commutated SCRs was limited, multi-phase choppers were sometimes employed to reduce the motor ripple current.

In1965,The concept of Fuzzy Logic (FL) was conceived by Lotfi Zadeh, a professor at the University of California at Berkley.This approach to set theory was not applied to control systems until the 70's due to insufficient small-computer capability prior to that time[18]. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement. Unfortunately, U.S. manufacturers have not been so quick to embrace this technology while the Europeans and Japanese have been aggressively building real products around it.

C.Era of MOSFET-Second generation power devices.

The advancement in the power electronics leads to the development of Power MOSFETs (Metal oxide semiconductor field effect transistor) with a high current gain is introduced in th mid of 1970's[19].The v/f control principle adjust constant volt-per –Hertz ratio of the stator voltage by feed foreword control. It serves to maintain magnetic flux in the machine at desired level .it satisfy only moderate dynamic requirement .High dynamic performance is achieved by field orientation ,also called Vector control. The technique called vector control can be used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke in 1972 [20] and further developed by Leonhard, opened up the opportunity for a.c. drives not only to match the performance of a DC drive but to improve upon it. The processing requirements were such that in its early days commercial exploitation was restricted to large drives such as mill motor drives and boiler feed pump drives. In the vector control scheme, a complex current is synthesized from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor. Essentially, the control problem is reformulated to resemble the control of a DC motor. Vector control offers a number of benefits including speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed. Future engineering development was thus inspired and was carried out during the golden age of DC motors. The term vector control was named in the sense of the control being based on the electric vector calculation of AC motors. This vector control has since spread on a worldwide scale, and has become the leading method used for variable speed drives in place of DC motor drives. Bipolar transistor technology also arrived,in 1970,which eliminated bulky auxiliary commutation circuits. [20].1972 Siemens launched the SIMOPAC integrated motor with ratings up to 70 kW. This was a DC motor with integrated converter including line reactors.The output voltage waveform of the PWM inverter contains miscellaneous harmonics and its precious analysis was reported by K. Takahashi and S. Miyairi in 1975. modern motor drive revolution began with the appearance of microprocessors.The first microprocessor was a 4 bit processor developed by intel in 1971.In the next year, an 8 bit processor is developed which is Intel 8008. The era of 16-bit Microprocessors began in 1974 with the introduction of PACE chip by National Semiconductor.The Texas Instruments TMS9900 was introduced in the year 1976. The Intel 8086 commercially available in the year 1978, Zilog Z800 in the year 1979, The Motorola MC68000 in the year 1980.[21],[24]. The neutral-point clamped inverter was invented in 1979[22]. Three-level inverters have attracted the attention of researchers since their introduction by Nabae.in 1981[26]. Ever since the invention of multilevel inverter topology namely Neutral-point clamped multilevel inverter in 1981 various three-level inverter topologies such as the capacitor-clamped inverters, H-bridge inverters and cascaded inverters have been proposed.A class of direct frequency changer (cycloconverter) operating on PWM principle has been forwarded from the beginning of 1980's that is also known as a matrix or Venturini converter. The converter can directly generate a variable-frequency variable-voltage wave for an ac motor drive with the line side power factor as unity (or programmable), but the lack of availability of ac switches with low loss, high frequency, and a bulky line side capacitor bank make the scheme somewhat unattractive.

The introduction of power transistors for implementing the bi-directional switches made the Matrix Converter topology more attractive .However, the real development of Matrix Converters starts with the work of Venturini and Alesina published in 1980 .They presented the power circuit of the converter as a matrix of bi-directional power switches and they introduced the name "Matrix Converter."[23].At the beginning of the 1980s, direct light triggering of thyristors was introduced [24].However ,the implementation of the direct light-trigger function into the high-voltage thyristor, and its efficient utilization for HVDC applications, became possible only recently when laser diodes became available and stable enough (with 30-year longevity) to be used in HVDC applications.Many power electronics researchers and engineers had an intuition that they could be applied to implement the software of adjustable speed motor drives. Intensive innovations and impovements were required before delivering a practical digital motor drive at the same level as that of the analog DC drive. The first fully digital DC drive was put into commercial operation in a cold tandem mill plant in 1981[25]. It has greatly contributed to the high quality steel production. It also made the work of troubleshooting easier by preparing diagnostic functions of data acquisition. In 1983 plastic mouldings made their first significant impact in drives. In 1983, the space vector modulation was introduced by Y. Murai and Y. Tsunehiro and has been applied to the analysis of the magnetic flux and to actual implementations as well.
The PWM technique utilizing space vector was introduced in 1983[27].

D.Era of IGBT - Third generation power devices.

A new power semiconductor device has been introduced which is designed to overcome the high on-state resistance of the power MOSFET while maintaining the simple gate drive requirements of that device.The introduction of the IGBT in the early 1980's has brought a visible change in the trend of power electronics. The mode of operation was first experimentally discovered by B. J. Baliga in 1983[28]. The IGBT is a hybrid device that combines the advantages of the MOSFET and the bipolar transistor. The device is slightly more expensive than the power transistor, but the advantages of higher switching frequency, MOS gate drive, the absence of the second breakdown problem, snubberless operation, reduced Miller feedback effect, and the availability of the monolithic gate driver with "smart" capability provides the overall system advantage to IGBT power converters. Because of higher switching frequency, ac drives can be designed without acoustic noise. The power rating and performance of the IGBT are continuously improving. IGBTs heralded the era of relatively quiet variable-speed drives. A device that is showing tremendous future promise is the MOS-controlled thyristor (MCT) which is developed in 1985[29]. The MCT is basically a MOS-gated thyristor that can be turned on and off by a small pulse on the MOS gate. The device was officially announced by GE in November 1987, when sample devices (50 A, 500 V/1000 V and 100 A, 500 V/100 V) were distributed. An MCT is comparable to the IGBT in switching frequency, but its lower conduction drop is a definite advantage. However, safe operating area of MCT is somewhat limited. Considering that it is a new device and there is future evolutionary improvement potential, MCT's are expected to have a significant impact in medium- to high power electronics.

When, in the mid 1980 s, it appeared that control systems would be standardized on the basis of the FOC philosophy, there appeared the innovative studies of Depenbrock ,Takahashi and Nogouchi ,which depart from the idea of coordinate transformation and the analogy with DC motor control. These innovators propose to replace motor decoupling with bang-bang self-control, which goes together very well with on-off operation of inverter semiconductor power devices. This control strategy is commonly refereed as Direct Torque Control (DTC) which is introduced by M Depenbrock and since 1984 it has been continuously developed and improved by many other researchers[31].In 1985, Isao Takahashi and Toshikiko Nogouchi proposes a scheme based on limit cycle control of both flux and torque using optimum PWM output voltage[32].
In 1986, at the IEEE's Industry Applications Society annual meeting, Divan proposed a new type of resonant link inverter when he presented his paper titled"The resonant DC link converter—a new concept in static power conversion"[33].In 1987 double-sided pwm rectifier-inverter with high performance GTO introduced by Kohlmeier[30].Mltsublshl Electric was the first to introduce the pioneering concept of Intelligent Power Module (IPM) in 1990, which has now become a reference in terms of power integration. The IPM integrates the IGBT power switch, along with its matched drive and protection circuits in an optimum modular housing[34].In the 1990s digital control using the integration of microprocessors became standard[35]. This large scale trend permeated quickly resulting in the development of high speed controlled semiconductor devices.Varispeed-616 G3 with 15kHz carrier frequency was produced from 1990. It was the world's first genuine low noise inverter which was not affected by jarring due to the electromagnetism noise of the motors. The last entry for U.S. multilevel inverter patents, which were defined as the capacitor-clamped multilevel inverters, came in the 1990s [37].Artificial Neural Networks (ANN) for electrical drives was introduced by Haykin in 1994 [35]. Fang Zheng Peng introduced cascade multilevel inverter in 1995 [38].In 1996, a new emerging technology for high power, low cost inverters, Integrated Gate-Commutated Thyristor(IGCT) introduced[21].1996 The first truly universal drive was launched that met the diverse requirements of a general-purpose open-loop vector drive, a closed-loop flux vector drive, a servodrive, and a sinusoidal supply converter with the selection purely by parameter selection. This was also the birth of what has become known as the intelligent drive with user-programmable functionality as well as a broad range of

Fieldbus connectivity. 1998 The integrated d.c. motor launched in 1972 was not a great commercial success – much has been learnt since those days. In 1998 integrated a.c. motor drives were introduced onto the market. These products are, for the most part, open-loop inverter-driven induction motors and were initially targeted on replacing mechanical variable-speed drives. Integrated servo motors followed. In 1998,direct power control (DPC) in PWM rectifier introduced by Toshihiko Noguchi and Isao Takahashi[39]. In 2000,direct-torque neuro-fuzzy control (DTNFC) scheme for pulse width modulation inverter fed induction motor drive are presented. More recently, several more multilevel topologies derived from the generalized multilevel topology have been proposed, including Marx multilevel inverter and zigzag multilevel inverters.

Fig 3: A low-voltage matrix converter is applied in an outdoor elevator for a building construction in 2011.

Fang Z. Peng introduces a new topology, Z-Source Inverter in 2002[40].The Field Stop IGBT (FS IGBT),a new power device concept with a great improvement potential introduced byT. Laska', M. Miinzer and F. Pfirsch,in 2000.[41] reverse blocking IGBT introduced by lindemann in 2001[42].The IPM (interior permanent magnet) motor is better suited for sensorless control. A saliency-based, sensorless drive of an adequately designed IPM motor for a robot vehicle was demonstrated by Yaskawa at Kitakyushu international airport in April 2006[40].A zigzag cascaded multilevel inverter topology,was introduced in 2008[42]. John.I.Rodriguez, introduced a new type of converter known as marx converter in 2006[43].

Recently,developments are going on Artificial Inteligence(AI) based intelligent control and estimation techniques, particularly with Neural Network(NNW), will also impact power electronics evolution. A large number of Artificial Neural Network(ANN) topologies yet remain unexplored for innovative power electronics applications. Besides, hybrid AI techniques, such as neurofuzzy, neurogenetic, neurofuzzy genetic, etc.,require systematic exploration. Development of large and economical ANN-ASIC chips is essential for industrial applications of intelligent systems. Currently, field programmable gate array(FPGA) are becoming very powerful with embedded DSPs[44]. Finally, modern control techniques are often based on the elimination or the reduction of number of sensors in power electronic applications. In this way, hardware sensors are replaced by software based on parameter identification, estimation, observation and/or signal injection.The challenge to present engineers and the motivation to future engineers lies in developing techniques, topologies and control methods that will result in more efficient conversion processes, both electrical energy to mechanical energy and vice versa.

III. CONCLUSION

Power electronics has established as a strong technological tool in drive technology and it will highly influence industrial development and economic competitiveness in near future. In spite of tremendous technology development in power electronics, the systems like fuzzy logic, neural networks, neurofuzzy, FPGA, direct torque control with space vector modulation etc. are the emerging technologies and the most researching area in motion control.

REFERENCES

1. "Highlights of ward leonard's seventy-five years of progress".pdf
2. "The development of power electronics in Europe",Dr. Frank Dittmann and Heinz Nixdorf.
3. "Fifty glowing years. The jubilee of the thermionic valve",Journal of the Institution of Electrical Engineers,vol.1 , pp.154 – 157,1955.
4. "High-Power Surges in Electric Distribution Systems of Great Magnitude",Steinmetz and Charles Proteus,American Institute of Electrical Engineers,vol.24, pp.297 - 315,1905
5. "De Forest and the first electrosurgical unit" Geddes, L.A. ; Roeder, R.A,Engineering in Medicine and Biology Magazine, IEEE ,vol.22 , no.1, pp84 – 87, 2003.
6. "The evolution of power electronics",Wilson, T.G.,*IEEE Trans.on Power Electronics*,Vol.15 , no. 3,pp.439 – 446, 2000.
7. "Static Scherbius system of induction-motor speed control" Smith, G.A., in proc. Institution of Electrical Engineers,vol. 124 , no. 6 , pp.557 – 560,1977.
8. "Methods of testing the Scherbius compensator",Ahmed, Abdel Aziz ,Journal of the Institution of Electrical Engineers,vol. 53 , no. 247,pp. 640 – 648,1915.
9. "Analyzing control system robustness" Simon, D., IEEE vol. 21 , no. 1, pp.16 – 19, 2002.
10. "The "Ignitron" Type of Inverter ,Wagner, C.F, Ludwig, L.R.,American Institute of Electrical Engineers,vol. 53 , no. 10, pp.1384 – 1388,1934.
11. "Electronic Speed Control of Motors" ,Alexanderson E.F.W., Edwards, M.A. ,Willis, C.H.,American Institute of Electrical Engineers, vol. 57 , no. 6,pp.343 – 354, 1938.
12. "A history of the invention of the transistor and where it will lead us",Brinkman, W.F. ; Haggan, D.E. ; Troutman, W.W., *IEEE Journal of Solid-State Circuits*,vol. 32 , no. 12, pp.1858 – 1865, 1997.
13. "A look inside the thyristor" Parker, J.H. Students' Quarterly Journal.vol. 41 , no.161, pp.147 – 149,1970.
14. "A low-noise Ku-band degenerate parametric amplifier" Whelehan, J., Moley, E. and Haber, I. *proc.of the IEEE* ,vol.51,no.8,pp.1140,1963.
15. "Discussion of Fabricated Aluminum Cage Construction in Large Induction Motors*", IEEE Trans. on Ind. Appl*.,vol. IA-13 , no. 6 , pp.626 – 627, 1977.

16. "Faster than a Speeding Bullet: An Overview of Japanese High-Speed Rail Technology and Electrification",Uzuka, T. ,Electrification Magazine, IEEE ,vol. 1 , no.1 , pp.11 – 20, 2013.
17. "Inverter Commutation Circuits", Humphrey and Andrew J.,*IEEE Trans. On Industry and General Appl.*,vol. IGA-4 , no. 1, pp.104 – 110,1968.
18. "Generic supervisory fuzzy logic control" ,Linkens, D.A. and Abbod, M.F. Two Decades of Fuzzy Control - Part 2, IEEE Colloquium., pp.1 - 5,1993.
19. "Power MOSFET technology",Lidow, A. ,Herman, T. and Collins, H.W. ,International Electron Devices Meeting, 1979 vol. 25, pp.79 – 83, 1979
20. "A new vector control scheme for an adjustable speed AC drive system utilising a high field permanent magnet synchronous machine " Bennett, N., Wang, J., Shimmin, D.W. and Binns, K.J. *IEEE,Sixth International Conference on Electrical Machines and Drives*, pp.121 – 126,1993.
21. "A History of Microprocessor Development at Intel" ,Noyce, R.N. ; Hoff, M.E. ,*Micro, IEEE* ,vol. 1 , no. 1, pp.8 - 21,1981.
22. "Recent advances in multilevel converter/inverter topologies and applications" ,Peng, F.Z. , Wei Qian and Dong Cao International Power Electronics Conference (IPEC), 2010 , pp.492 – 501,2010.
23. "Experimental analysis of a matrix converter prototype based on new IGBT modules" ,Casadei, D. ,Serra, G., Trentin, A., Zarri, L.and Calvini, M. ,*IEEE Conf.On Ind. Electronics*,vol. 2 , pp.559 - 564 ,2005.
24. "Directly light triggered 8KV-1, 2KA thyristor" ,Ohashi, Hiromichi ,Ogura, T. and Yamaguchi, Y. *IEEE International Electron Devices Meeting*, 1983 ,vol. 29 , pp.210 – 213.
25. "Digitally Controlled DC Drive Motors" ,Jing-Ping, Jiang and Marleau, Richard S. ,*IEEE Trans. on Ind. Appl*.,vol. IA-18 , no. 6,pp.728 - 735 ,1982.
26. "Three phase three-level PWM switched voltage source inverter with zero neutral point potential" ,Won-Sik Oh ,Sang-Kyoo Han ,Seong-Wook Choi and Gun-Woo Moon , IEEE 35th Annual Power Electronics Specialists Conference,. PESC 04. 2004 ,vol. 6, pp.4405 – 4410.
27. "Phase space vector modulation for a four-leg voltage source inverter" ,Bekbudov, R. 14th International IEEE Power Electronics and Motion Control Conference (EPE/PEMC), 2010 ,pp.T2-36 - T2-43
28. "The insulated gate transistor: A new three-terminal MOS-controlled bipolar power device" Baliga, B.Jayant ,Adler, Michael S.,Love, R.P. ,Gray, P.V. and Zommer, N.D. , *IEEE Trans. on Electron Devices*,vol. 31 , no. 6, pp.821 – 828, 1984.
29. "MOS-Controlled thyristors—A new class of power devices", Temple, V.A.K., *IEEE Trans. On Electron Devices* ,vol. 33 , no. 10, pp.1609 – 1618, 1986.
30. "Highly Dynamic Four-Quadrant AC Motor Drive with Improved Power Factor and On-Line Optimized Pulse Pattern with PROMC", Kohlmeier, Helmut ,Niermeyer, Olaf , Schroder and Dierk F. , *IEEE Trans. on Ind. Appl*.,vol. IA-23 , no. 6, pp.1001 – 1009, ,1987.
31. "Direct self-control (DSC) of inverter-fed induction machine" Depenbrock, M., *IEEE Trans. on Power Electronics*.,vol. 3 , no. 4 , pp.420 – 429, 1988.
32. "A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor" ,Takahashi, I. and Noguchi, T. , *IEEE Trans. on Ind. Appl.*,vol. IA-22 , no. 5 , pp.820 – 827, 1986.
33. "The resonant DC link converter-a new concept in static power conversion" ,Divan, D.M., *IEEE Trans. on Ind. Appl.*,vol. 25 , no. 2 , pp.317 – 325,1989.
34. "Latest technology improvements of Mitsubishi IGBT modules" Medaule, D.,Arita, Y. and Yu, Y. ,*IEEE Colloquium on New Developments in Power Semiconductor Devices*, pp.1 -5,1996.
35. "An integrated digital controller for brushless AC motors using a DSP microprocessor" ,Garate, I. ,Carrasco, R.A. and Bowden, A.L. *IEEE Third International Conference on Power Electronics and Variable-Speed Drives*,pp.249 – 252,1988.
36. "Two-phase modulation technique for three-level inverter fed AC drives" ,Halasz, S., Huu, B.T. and Zakharov, A. 9th Mediterranean Electrotechnical Conference, MELECON 98.,vol. 2 , pp.1209 – 1213,1998.
37. "Multilevel inverters: a survey of topologies, controls, and applications" ,Rodriguez, J. , Jih-Sheng Lai and Fang Zheng Peng ,*IEEE Trans. on Ind. Electronics*, vol. 49 , no. 4 ,pp.724 – 738,2002.
38. "A multilevel voltage-source inverter with separate DC sources for static VAr generation" Fang Zheng Peng , Jih-Sheng Lai , McKeever, J. and VanCoevering, J., *Thirtieth IAS Annual Meeting on Ind.Appl.,IEEE*, vol. 3 ,pp.2541 – 2548,1995.
39. "Direct power control of PWM converter without power-source voltage sensors",Noguchi, T.,Tomiki, H. , Kondo, S. and Takahashi, I. *IEEE Trans. On Ind. Appl*., vol. 34 , no. 3 ,pp.473 – 479,1998.
40. "Saliency-based Sensorless Drive of Adequate Designed 1PM Motor for Robot Vehicle Application" ,Ide, K. ; Takaki, M. , Morimoto, S. , Kawazoe, Y. , Maemura, A. and Ohto, M. ,Power Conversion Conference - Nagoya, 2007. PCC '07 ,pp.1126 - 1133 ,2007.
41. "A simple direct-torque neuro-fuzzy control of PWM-inverter-fed induction motor drive" Grabowski, P.Z. , Kazmierkowski, M.P. , Bose, B.K. and Blaabjerg, F., *IEEE Trans. On Ind. Electronics*, vol. 47 , no. 4 pp.863 - 870,2000.
42. "A zigzag cascaded multilevel inverter topology with self voltage balancing" ,Fan Zhang , Shuitao Yang , Peng, F.Z. and Zhaoming Qian. Twenty-Third Annual *IEEE Conference* on *Applied Power Electronics and Exposition*, pp.1632 – 1635,2008
43. "A multilevel inverter topology for inductively-coupled power transfer" ,Rodriguez, J.I. ; Leeb, S.B., Eighteenth Annual *IEEE Applied Power Electronics Conference and Exposition*, vol. 2 , pp.1118 - 1126 ,vol.2,2003,
44. "FPGA Design Methodology for Ind. Control Systems—A Review", Eric Monmasson and Marcian N. Cirstea, *IEEE Trans. On Industrial Electronics*, vol. 54, no. 4, 2007.