Literature Survey on Variable Frequency drive

Anuradha Tomar
Electrical & Electronics Department
Northern India Engineering College,
NewDelhi, India.

Devesh Singh
Research & Development Department
Prabha Electronics & Automation
Ajmer, India.

Abstract— **Every nation, as a policy decision; has put a thrust on the mass production of quality products for the easy availability to the each section of the society. Automation and motion control are prime factors to run an industry. This paper surveys the literature of the Variable Frequency Drive. Total 66 papers are considered here and year wise description is mentioned for better conceptual knowledge and understanding. The paper should prove useful to both researchers as well as practicing engineers as a signpost to the current state of the art.**

Keywords-Variable Frequency Drive, Literautre survey.

I. INTRODUCTION

The drive is a general term responsible for controlled motion with specific start/stop and matched torque properties as required by the process, keeping input energy level at most minimum level while keeping efficiency to be the best one; in other words minimizing the losses. The drive could be alone or a combination of mechanical, hydraulic, pneumatic, electrical motors combined with control elements like gearbox, belts and pulley drives, chain drives, throttle valve, pressure regulator, and electronic systems with analog/digital controls. Almost 80% industrial motions are achieved by asynchronous induction motor. Thereby there is increasing population of AC digital drives replacing DC drives and simplifying mechanical drives.

II. LITERAURE SURVEY OF VARIABLE FREQUENCY DRIVE(VFD)

Dennis P. Connors [4], illustrated various type of Variable frequency drives (V.F.D) with their limitations. Basic relationships among drive voltage, frequency, torque, speed of motor along with harmonic effect were described. Emphasis on detailed application requirements and decision on drive ratings etc., considering environmental factors like altitude, temperature and types of driven loads, were outlined.

Ibrahim D. Hassan [13], basic principle of Adjustable speed drive (ASD) followed by methods of specifying ASD and its basic components were covered in detail. Benefits of prevailing standards like NEMA for motor and ANSI C50.41, ANSI C34.3- Part I for thyristor converter and ANSI/IEEE 519 for motor drive; to end users; were found to be limited. Further he presented review on calculating various parameters and performance factors.

Thomas A. Lipo [16], summarizes various stages of developments of VFD, linked with technological innovations in power components, like silicon controlled rectifier (SCR), gate turn off thyristor (GTO), MOS controlled thyristor MCT, insulated gate bipolar transistor (IGBT), Pulse width modulation (PWM) controlled. Effects of high frequency link circuits were presented. Development in current regulated stepper motor with their limitation of generating spikes was discussed. A detailed overview of synchronous reluctance brushless DC motor drives is presented.

Robert A. Hanna [19], discussed the primary source of current and voltage harmonics and their effects on input supply network and driven plant and machineries. Method of acceptable harmonic distortion limits were given, so that user can safely apply on their driven motors. Few working examples of motors were given to illustrate temperature rise effect on class B and F insulation of winding along with laminated rotor. However addition of filters; cooling fans; changing 12 pulse from 6 pulse converter, ensuring unbalance to balance load conditions; providing proper system impedance valves, can reduce both harmonical order and their magnitude, solely responsible for efficiency of driven machine.

Paresh C. Sen [20], describes the substitute of DC drive performance by AC frequency drive was possible, as a result of sustained research work in area of power electronic components and micro-controllers. Various types of control schemes for flux and slip control, in induction motor were illustrated. Basic principle of torque and air gap control by splitting two components of stator current as I_d and I_q was discussed in detail. The nonlinear nature was linear zed by d-q vector coordinate method, similar to armature and field control of a DC motor. Relevance of Kramer drive and cyclo-converter in scherbius methods was touched to show that bidirectional power flow allows operating the drive in both below and above synchronous speed. Synchronous motor drives and permanent magnet synchronous drives were also described. Lastly PWM based voltage and current control schemes were described with their merit/demerit and application areas. Recent methods like "Bang-bang current control schemes" where feedback of phase current is compared to preset reference in such a manner that a fixed current band can be maintained. Adding new reference link for switching at zeros crossover makes the switching loss most minimum and device ratings can handle higher power. As per author the future of resonant link converter is bright in coming times.

Jon W. Simons and Daniel A. Dey [26], a vendor understands the capability of drive while user knows the application requirement of process. Both things can be utilized by writing software, which need application description, the basic document for better understanding by all team members. The outlines include definition of terms used, system configuration using block diagrams and its overview and interface with drive signal input/output without hardware details. Normally steady state performance requirements cane is met, but dynamic response and performance of process is to be defined carefully with possible under and over limits.

Many a time's process data are not available and choice goes for adaptive control. Response of commands given by operation should be reflective in action within 0.5 second. Mechanical data like speed, torque, moment of inertia, start-up acceleration and stopping deceleration tension levels applicable for today and tomorrow should be worked out/estimated with concerned users.

Hardware specification like, power supply voltage, enclosure, ambient temperature, humidity level, interface with local/remote controllers, cable length limitations, grounding requirement, protective elements like fuses overload, contractors, MCB, cable size, safety features etc. should be specified. Training on use of drive features should be arranged, to exploit full features and capabilities for process control.

W. Leonhard [34], electricity is generated, transported from natural resources to end users after a series of transformation and processing and thereby is very precious; so its conservation is automatically very important to us. Wide applications include from minute mechanical printers to gearless mineral ore mill with torque span up to 1000000 Kg.m. He predicts that energy cost in European continent is more than in America; and that is single reason responsible for high densities of AC drives in Europe. Further illustrations of various areas of intensive research are highlighted.

Tabulation of electrical machine with corresponding possible combination of various types of converter and inverters are given along with full power range indication. The controlling parameters responsible for torque quality, magnitude and momentum of machine were discussed. A clear relationship between angular displacement, flux and ampere turns was discussed, through theory of vector orientation and their I_q , I_d components. Nonlinear expressions for AC machines were developed and estimation of speed, torque and electrical signals, leading to "Encoder less Drives" were given and verified by experimental results.

P. Y. Keskar [35], based on IEEE 519-1992 standard on Variable frequency drives (VFD) voltage and current harmonic order and their magnitude calculation methods were shown. Tabulation for distortion limits as per standard and effects on utility with user's limitations were discussed. Before installing VFD, appropriate harmonic analysis and mapping on impedance line diagram of plant could be powerful tool in deciding VFD hardware and other filters location.

James Will Gray and Frank J. Haydock [36], presented fundamental concept of harmonics, usual sources of harmonics and probable frequencies of harmonics, based on theory of energy balance and Fourier series analysis. For a 6 pulse converter ($6n \pm 1$) frequencies of harmonic current will be generated and their magnitude is inversely proportional to harmonic number for ideal squarewave. These switching pulses and harmonics are superimposed on fundamental wave and produce distortion. Any switching device and nonlinear load such as switch mode power supply, electronic ballast, uninterruptable power source (UPS), AC/DC drives rectifier, and any wave converter are sources of harmonics.

Basic effect of any harmonic is heating and insulation weakening process. Heating is due to flow of positive and negative sequence of current in a electrical machine. ($k\,n + 1$) are positive sequence phase current and ($k\,n - 1$) are negative sequence phase current, here k is pulse number of converter. For a 6 pulse (3 phase bridge) converter 7^{th}, 13^{th}, 19^{th} are positive sequence current, while 5^{th}, 11^{th}, 18^{th} are negative sequence current. In induction motor, 5^{th}harmonic which is negative sequence current produces MMF in opposite direction to fundamental hence motor torque is reduced. Further these harmonic current causes torque pulsations, heating due to high frequency eddy current, hysteresis and skin effect losses in winding.

Total harmonic distortion (THD) is an index of quantity of harmonic presence. It is measured at point of common coupling and expressed as ratio of RMS of harmonic content to RMS of fundamental. Higher THD value may create resonance in electrical network by exciting capacitance and reactance components. Higher power drive range (300-1000 H.P.) is built around current sourcing due to magnetic field of reactor of DC bus. Here harmonics are in form of load commutation notches. A detailed harmonic study questionnaire was illustrated. Computer simulations based on popular software such as HARMFLO, EMTP (Electromagnetic transient program), TACS (transient analysis and control system). EMTP is widely used to study transients in power system related items like single/ multiphase, balance/unbalance load circuit breaker, transformers, rotating machines, transmission lines etc. General methods for harmonic reduction are adding line impedance by reactor or isolation transformer active/passive filters and phase multiplication.

An example for deciding line reactor as per IEEE-519-1992 is illustrated for readers. Shunt filters consisting of RLC elements are passive filters used for filtering 5^{th}, 7^{th}, and 11^{th} harmonic. As shown by comparative waveform by multiplication of 3 phase system (6 pulse) to 12 pulse using additional input transformer with delta/star connections having 30° electrical phase shift, was found effective for eliminating current pulses.

Peter W. Hammond [38], improvement in torque strength with reduced pulsation; supply power factor, and its quality in terms of low harmonic presence; reduced voltage peaks on motor winding insulation; and absence of zero sequence voltage are the basic points, under illustration, given by the author. 18-pulse or better configuration with isolated transfer of converter ensures below 3% harmonic while for 30-pulse drive it is below 1%; at 10% loading on drive. Waveform and patterns at different loading percentage to show extent of improvement are shown.

Robert A. Hanna and Shiva Prabhu [39], data pertaining reliability and performance of VFD system with associated components shared by power provider and users were collected and shared with drive manufacturers. Survey questionnaires to perspective users and manufacturers were framed, covering motor, drive details, selection and application criteria's, mechanical driven equipment, line transformer and harmonic filters, etc. others points included were support from manufacturers, diagnostic system, harmonic and mechanical vibration; noise level, space limitation, environmental control, effects on power network and ultimate success of installation and payback periods.

Information from manufacturers were technology oriented on converter, heat generation, alarms for failure, market consumption, price per H.P., protection features, isolation of control power circuit, failure causes, diagnostic methods, spares, support and services, involvement during application and retrofit including presale support etc. An abstract of findings and general observations were given. Number of components failures and their periods for example like control power supply, logic board, power devices, incorrect protective settings, etc. were enlisted. Cost of repairs during warranty and later were also indicated.

74% drive were with 12/6 pulse design, while 6/6 pulse design were 23%. 95% of drive had the provision of UPS to reduce disturbance. 83% of drives were wired to run motor directly without drive in case of breakdown. 70% of drive failure was due to component failure, while 50% tripping due to supply under/overvoltage problem. 40% fuse failure and 43% control card failure were reported. 13% problems were due to control power supply failure and protective settings at acceleration and deceleration of drives. Mechanical problem were negligible. 73% drive application was from pumps, 15% from compressors and 12% from fan/blower control. 49% payback period was 2-3 year and 31% quoted 3-5 year. Reliability was reported as 77%. 82% users conducted harmonic analysis, to ensure power supply conditions, noise level of VFD at 1 meter distance varied between 70-85 dB. Various suggestions and recommendations were given to users, utility suppliers and manufacturers.

Thomas M. Jahns and Edward L. Owen [45], historical review on development of AC drive beginning from 1920, when devices like mercury arc rectifier, thyratron and ignition were used; was given with due importance to key concepts used in speed control till 1957, i.e. the arrival of thyristor technology. In 1901, Mr. Peter Cooper Hewitt demonstrated rectification using mercury arc rectification. Brief development progress on devices like thyratron, ignition were discussed. Wound rotor induction motor with external slip rings, were basis of speed control by varying voltage at wound rotor using normal voltage controller; external tapping change of resistance box by contactor is popular even today to vary the speed of synchronous motor.

In 1901, Krammer control system was successful in controlling heat losses in resistance method. In 1907, scherbius system was an alternate speed control system, which was aggressively used. In 1914, Schrage brush shifting motor was another integration to overcome multi-machine concept, mainly used in textile mills up to year 1960. Ward Leonard speed control system was another milestone. In 1935, a team of Brown Boven engineers developed synchronous motor using excitation from single phase AC for locomotive up to 2400 KW. 1930, G.E. engineers developed thyratron based synchronous motor drive. With the advent of thyristor in 1957, inverter application caught significance speed. Past generation drives were a never ending process and as such new solutions are awaited.

Sidney Bell et. al.[46], presents experimental data to exhibit damaging effect of electrical discharging from VFD. Keeping fairly constant other variables like speed, loading fitting tolerances, lubrication temperature, dust, vibration and foundation leveling etc., PWM based inverter harmonics gets discharged through capacitive film of grease between conducting parts. It was demonstrated that motor failure occurrence was 7 times and grease lost natural color and lubricating properties, apart from minute pitting marks on bearing inner and outer races including balls. Induced rotor shaft voltage, results circulating bearing currents which is limited by bearing impedance. Bearing resistance is low at low speed and gets mega ohmic value at higher speed (above 100 RPM). It is like a film capacitor, coupling between stator and rotor. The lower carrier frequency of VFD gives better life. Peak shaft voltages also reduced if drive system voltage is low. Bearing current, waveform and voltage measurements were conducted between stator neutral, ground, rotor shaft and ground by oscilloscope. Use of R-L-C filter, output line reactor, reduced the damage as harmful factors like dv/dt and EDM discharge were limited. Use of higher switching frequency with zero voltage switching and resonant techniques eliminate harmonics and hence effect on better bearing life. A non-magnetic electrostatic shield between rotor and stator winding, eliminate capacitive coupling. Several large size bearing manufacturers offer ceramic or polymer coating on outer race to minimize the EDM damage. Grounding bushes are installed externally to the motor, to shunt out grounding current and seems to most effective method.

Alessandro F. Moreira et.al.[48], presented study of frequency response and over voltage phenomenon due to steep pulse rise time; when gets propagated on a long cable motor drive. First, frequency characteristics on cable and motor impedance were obtained and their suitable simulation models were developed; analyzed on MATLAB; and compared with experimental results. The models can predict accurately a better dv/dt filter for a long cable motor, connected to PWM inverter drive. Line impedance under short circuit condition and open circuit impedance between phase and neutral over full frequency range from low (100 Hz) to high (MHz) were calculated, over on one meter length for various cross sections and compared with experimental data. Model for Input impedance of AC motor was developed over full frequency range, taking parameter like phase to neutral impedance (Z_{ph}) and phase to ground impedance (Z_{pg}), with both delta and star configuration. Other parameters like winding turn resistance, inductance and capacitance (R_t, L_t and C_t) and R_e for eddy current losses were considered. Based on above parameters, models were fed in MATLAB software and it was observed that theoretical and practical graphs were in full agreement for a 3 H.P. motor.

F. Naceri and L. Abida [52], in case of “ON line tunning” with vector control AC drive slip constant knowledge is must, so that error between calculated torque and load torque is minimized. Lorentz and Lawson provided a solution to above task by MRAC (Model reference adaptive control) model. Here, authors proposed an extension to above, without involving necessity to know plant model and without calculating controller gains, hence name was given MCS (minimum controller synthesis). This algorithm of vector control method of AC drive is independent of unknown plant variables, external disturbances and other nonlinear behavior existing in surroundings. A series of theoretical equations have been derived to develop an algorithm, for maintaining stability of closed loop control system including feedback and reference, in such a manner that no external plant disturbance can influence the drive performance. Adaptive control scheme against external disturbances or systematic load change conditions is developed, by tracking the situations continuously. The various gain stages of closed loop control system like feed forward and feedback gain changes during speed transients and speed reference changes but not during steady state conditions. It was shown that for sudden change of load, both above described gains are changed and gets adapted to new condition. During transients the error is significant between developed model and real system, but reduces to zero during stable conditions with response time 0.2 second.

R. Champagne et. al.[53], field supply and load conditions can be realized in laboratory, without usage of expansive high power test benches and machine. A number of complex features like vector control (flux oriented speed and torque control), on line self tunning, adaptive to motor name plate rating parameters, fault generation, detection and diagnostic applications are to be simulated and tested with fully secured and safe methods. Authors tried to develop a universal drive model, consisting of nonlinear blocks and elements like stator/rotor winding currents, link inductor, capacitor voltages, and machine power generated and load torque, moment of inertia, pole pairs of motor etc. To verify the above model, an experimental set up was used with PWM based voltage source inverter with 4 KHz switching frequency for a fan type load. C language program software included machine parameter values like nominal power, voltage frequency, stator and rotor resistance, mutual inductance, stator and rotor leakage inductance, combined rotor and load inertia, friction and number of pole pairs. DC source voltage, PI controller, proportional gain and integral gain, were programmed in Motorola MC68332 microcontroller. The simulator part, output gate signals were isolated by Opto-couplers and IGBT were switched on, after removing drive control part. A graph between motor shaft RPM, against both real time simulation and offline control were plotted and found in close accuracy with matching response for electrical and mechanical variables like current and torque. Based on above it is clear that real time simulation is a good alternative to test drive functions.

Aníbal T. de Almeida et. al[55], variable speed drives are considered to have highest energy saving potential and widely replacing mechanical, hydraulic and DC motor speed control system. Thirdly, VSD performance is useful in process control with minimum wear and tear in driven equipment. Low noise, infinitely speed/torque variation are other features, which establish them as new motor technology in industries. In pump applications consumed power is proportional to cube of speed, hence VSD replaces throttle valve, with large energy savings. In pump station, “water hammer effect causes pipe leakage and seals breakage, but with VSD, pipe joint life is improved due to controlled acceleration/deceleration. In fan control, energy wasted by throttling the air flow, is saved by VSD. Input valve control linked with outlet damper is the worst case and VSD can provide significant energy saving in range 25-50%. Compressors load is a constant torque application, which may save up to 30%, at partial loads demand of 50%. In a refrigeration compressor, cyclic on/off can be replaced by VSD which have better temperature control with large energy savings (25%). In elevator and lifts, VSD with regenerative capability, energy can be feedback to supply grid. Machines with high inertia, involving frequent start/stop with braking operations; significant energy saving are realized. Conveyors need constant torque against friction, for a given speed and weight on it, hence energy saving is proportional to speed reduction.

L. Szentirmai and T. Szarka [57], presented spectrum of industrial growth from 1930 and based on interaction on sharing of information and technology, globalization process has attained good momentum. There are better joint efforts and cooperation among universities, research institutes, industries, other professionals and a "knowledge based society" had already begun. In June 2000, Lisbon summit identified; the need of research for generation, transmission, communication and exploitation in all area of advancement of human being, through education and manpower training. For sustainable development of society, resources are limited. Economic energy consumption is the need of the day and more for future. Energy resources include 8 million tons of oil equivalents per day for electricity generation. Annually, about 1200 TWh (Tera Watt hour) electricity is consumed by the total population of world and 55-70% energy share is attributed to electrical drives ranging from microwatt motors in bio-medical applications to megawatt power drives in ship, compressor, oil offshore and industries. In a general industry, 66% energy is consumed by motors. World drive growth rate is 7 to 10% per annum.

In drive areas, application of space vector theory is replacing electric-magnetic circuit theory, by software based modeling, simulation and testing for enhancing reliability; inbuilt fault identification and possible correcting mechanism their itself. Author put forward requirement of intelligent motor drive such as self supervised operation; human machine interface (HMI); self service ability; self protection; adjust working to environmental conditions and all at low cost, with energy efficient, reliable, compact size, rich features and high performance. An example of continuous cast control by drive system was described. In second drive application example, computerized diagnostic could determine the cause of failure of mechanical shaft due to resonance of pulsating torque and mechanical system at 10 KHz system were matched. By increasing switching frequency to 12 Hz, problem was solved. There is need for new theory, hypothesis and application for building modules, simulating test algorithms and artificial intelligent fuzzy models with sensor less drive technology. Combining advancement of power electronics, control and computer engineering will boost the drive development touching new heights.

T.N. Date and B.E. Kushare [60], studied through lab tests the effect of unbalance (1-3%) phase supply, with voltage sag and interruptions, under different loading conditions, on 6 pulse AC drives. The next part included was the effect of using line reactor, on harmonic elimination, under varying loads on motor. The line reactor slows down capacitor charging rate (di/dt), as a resultant current is drawn over a longer period and current transients of high frequencies are blocked. The set up included 7.5 KW drive, motor and power quality analyzer model HIKOI3196. By inserting 3%, 5% and a combination of 3% DC choke and 5% AC reactor, 5th harmonic magnitude was 39%, 32% and 27% respectively. Under above set up 7th order harmonic reduced to 17%, 12% and 19%. 11th order harmonic was of the order of 7%, 5.8% and 4.5% respectively. Line reactor effectiveness is reduced at part loads; hence dimensioning the size of reactor is dependent on percentage load conditions of motor. With increased phase unbalance at drive input, additional current harmonics were found.

Cursino Brandão Jacobina et. al.[61], an application where eight motors and drives are connected in such a manner that normally required inductors and switches are reduced, while keeping power factor and bidirectional power flow controls, with minimum space requirement. A number of drive configurations, with reduced number of switches and booster inductor were proposed and mathematical equations were developed, solved and conclusions were drawn with tabulation of resultant data. Torque control was possible by varying either dq current or dq voltage, while power factor control by varying power current from DC grid. It was noted that there was increase in power loss, as current per phase was increased; However during unbalanced load conditions negative sequence voltages were generated. Zero sequence current did not contribute to air gap Magnetic Motive Force (MMF).

José Rodríguez et.al [62], presented a review on development of high power converters with three multilevel topologies like neutral point clamped (3L NPC), flying capacitor (4L FC) and cascaded H bridge (CHB), Gate turn off (GTO), Insulated gate-bipolar transistors (IGBT) and Gate commutated thyristors (GCT) came into existence in 1980 and 1990 respectively, with reduced power losses, simple gate control without using snubbers and better switching functions. A number of medium voltage application were tabulated, with scope of energy saving and better performance control. It was told that payback period for investment was one to two and half year. The drives with cycloconverter were used in high power application, with bidirectional power flow. Another scheme includes current source and voltage source inverters with DC bus keeping filters on motor side (optional). Various configurations with block diagrams were shown and discussed. IGBT modules up to 3.3/4.5/6.5 KV are available by cascading in series with common gate control. Film capacitors are normally used as DC bus filters to minimize harmonic current.

Neutral point clamped (NPC) voltage source converter (VSC) or diode clamped topology is important as power devices work at half the DC bus voltage. Input transformer with 6/12/18/24 pulse rectifier improves DC bus and power quality, by reducing harmonic order and their magnitude i.e. total harmonic distortion (THD) level. The 3L NPC-VSC (3 level switch in series with neutral point clamped voltage source converter) configuration is suitable as active rectifier and allows four-quadrant with regenerative braking and power factor correction. This topology is widely used as Medium voltage drive in industry both with IGBT and IGBT modules. Water, chemical metal, power, mining oil and gas are popular application areas.

Cascaded H-bridge (CHB) topology is suitable for high power drives (say 12KW, 1200 Amp.). One cell of CHB consists of independently isolated secondary source displaced by 60° to reduce input harmonics; 3 phase diode bridge, a capacitive dc link; depending upon DC voltage and power level of drive. Suitable numbers of such cells are joined to form a complete cascaded bridge. PWM method, with common reference signal base, a phase shift (180°/K, where K is no. of cell) is introduced to trigger all associated power cells, to achieve stepped staircase multi level waveform at common carrier frequency. It is noted that power is evenly distributed among all cells due to common reference and carrier frequency.

In flying capacitor with four level voltage source converter (4L FC-VSC), one unit/cell consist of 3 IGBTs connected in series suitable for $1/3^{rd}$ of DC bus voltage. Nominal voltage level of flying capacitor is maximum $2/3^{rd}$ of DC bus as per circuit location. The upper and lower commutating IGBT gate pulses are positive gS_1 and inverted gS_1 for upper and lower part of phase current and have been tabulated. For a four level topology, there will be 4^3 = 64 different switching states. In this case also, PS-PWM i.e. phase shift-pulse width modulation technique is preferred, but phase shift is 360° /K, as compared to 180° /K in CHB. Another difference is that flying capacitor (FC) is bipolar (both positive and negative part) while CHB is unipolar (only positive). Up to 4 MVA power, 6KV drive had been applied, using 6.5 KV, 600 Amp. IGBT modules.

Marc Hiller Et.al.[63], presented overview and comparison of medium voltage (MW) drive, characteristic, complexity and number of power devices involved. Low voltage range drives are up to 690V and up to 300 KW. MV range starts approx. from 300 KVA to 2 MVA with standard output voltage 2.3/4.16 KV in North America and 6-6.6 KV in Asian and Russian market. High power drive range starts from 2 MW and highest figure is 25 MW at 6.5 KV. All above drives are based on IGBT and IGCT (Insulated gate commutated thyristor) with different configurations and topologies. Further higher ratings, say 2 MVA to 60 MVA are working at output voltage which can be freely selected and whole drive system cost depends upon input line transformer, converter, switchgears, cable and motor.

3L-NPC are based on IGBT (6 MVA, 2.3 KV-7.2 KV), IGBT press pack (9MVA, 3.3 KV) and IGCT (10 MVA, 4.16 KVA), with switching frequency range 0-250 Hz. IGBT based drives preferred in area of pumps, blowers and extruders. Press IGBTpack (PP-IGBT) and IGCT are preferred in high power drives in rolling steel mills with fluctuating load. Load commutated inverters (LCI) are based on thyristors (2.5-70 MVA, 1.8-12 KV) working at switching frequency 0-105 Hz in area of compressors and marine propulsion/turbine drive. 4L-FC and 2L-CHB are based on IGBT (5.8 MVA, 2.3-6KV) for above described application, at higher switching frequencies (0-3000 Hz). Cyclo-converters (CC) are based on thyristor (3-25 MVA, 1-4 KV), with switching frequency (0-22 Hz i.e. 50% of line frequency) and are used in ball mills, cement mills and rolling mills.CC is the only topology which does not involve any energy storage device.

With developments in silicon technology, now silicon is more pure and homogeneous and wafer area can be increased sufficiently to withstand short circuit level without arcing and even without fuses. Thyristor device ratings starting with 1965 (40 Amp. 1350 V), 1980 (1400 Amp., 4200V), 1990 (2600 Amp., 5200 V) and in year 2000 (3000 Amp., 800 V) have largely improved. Monitoring of gating signals, state of thyristors etc. is possible. Availability of modular structure with very large current and voltage rating, reliability and low cost make them suitable even after 50 years of industrial use. IGBT are suitable for low and medium power range due to its switching control, without snubber. Another advantage is its use in series making suitable up to 7.2 KV rpm.

"Silicon area per Megawatt" output power is an index for drive cost. Due to more "On state losses" and switching losses IGBT require larger silicon area and it is costlier, in comparison to IGCT. Cascaded H bridge (2L CHB) with low voltage IGBT (1.7 KV) need much less silicon area as compared to high voltage IGBT. Due to lower number of switching elements and using lowest, silicon wafer area; LCI will continue to be in market in high power application. Comparing to Voltage Source Converter (VSC), silicon area of CC topology is comparable and will continue to be used in special applications like steel rolling and ball mills.

Joseph Song-Manguelle et.al. [64], discussed the predictive causes of mechanical shaft failures when driven by 3L-NPC (3 level Neutral point clamped converter) 35 MW converter drive system. Pulsating torque developed within motor air gap; is one of major factors, causing torsional resonance and vibration in driven shaft couplings. Relationship among current harmonics with vibrating air gap causing torque harmonics and torsional resonances were studied, by building mathematical models. Test was conducted on compressor test bed coupled to a motor and driven by PWM based 3L-NPC, 35 MW inverter. Such results were compared with theoretical model and found to be in order.

It was observed that mechanical shaft failure is due to frequency of PWM drive's pulsating torque and not their magnitude. Further, these air gap flux pulsations are the result of current harmonics, so generated from inverter and flowing into motor windings. An analogy for angular rotation to current; torque to voltage measured from ground; moment of inertia to inductance; friction and other speed damping factor to resistance; Inverse of stiffness to capacitance was considered for mathematical modeling. In this way mechanical and electrical oscillations can be analyzed on a common platform as if an electrical circuit is made from R, L, C elements and such equations and relationships could be solved by polynomial differential equation.

It was shown that any torque harmonic located, near to shaft natural frequency will resonate and will create accelerated fatigue or damage, if it is damped. Experimental data put on graph shows a simple and direct relationship between current and air gap torque harmonic frequencies.

REFERENCES

[1] Robert G. Schieman, Edward A. Wilkes, and Howard E. Jordan, "Solid state control of Electric Drives", Proceeding of the IEEE, Vol. 62, No. 12, December 1974, pp. 1643-1660.

[2] R. P. Stratford, "Harmonic pollution on power systems-A change in philosophy," IEEE Transaction on Industrial Application, Vol. IA-16, no. 5, pp. 617-623.Oct. 1980.

[3] R. P. Stratford, "Harmonic pollution on power systems-A change in philosophy," IEEE Transaction Industrial Application, Vol. IA-16, no. 5, pp. 617-623, Oct. 1980.

[4] Dennis p. Connors, and Dennis a. Jarc, "Application considerations for AC drives", IEEE Transactions on Industry Applications, Vol. IA-19, no. 3, pp. 455-460, May/June 1983.

[5] IEEE Std. 597-1983, "IEEE Standard Practices and Requirements for General Purpose Thyristor DC Drives."

[6] R. E. Sabaski, "Grinding mill drives: Systems, challenges, considerations," Mining Eng., pp. 43-47, Jan. 1983.

[7] Deken, Kenneth F., "Dealing with line harmonics in PWM variable frequency drives", I&CS, April, 1983.

[8] Kloss, Albert, "A Basic Guide to Power Electronics", John Wiley & Sons, New York, 1984.

[9] Armando Bellini, Gennaro Figalli, and Michele La Cava, "A Discrete Feedback Suboptimal Control for Induction Motor Drives", IEEE Transactions on Industry Applications, Vol. IA-1. NO. 2. pp. 422-428, March/April 1985".

[10] J. Arrillaga, D. A. Bradley, P.S. Bodger, "Power System Harmonics, John Wiley & Sons, New York, 1985.

[11] Robert Schieman, P.E., "AC Harmonics Easily Identified, Nullified, Power Transmission Design, November, 1990.

[12] ANSI/IEEE Std.-995-1987, "IEEE Recommended Practice for Efficiency Determination of Alternating- current Adjustable-Speed Drives Part I-Load Commutated Inverter Synchronous Motor Drives".

[13] Ibrahim D. Hassan, "Specifying adjustable-speed AC drive systems and currently available Industry Standards", IEEE Transactions on Industry Applications, Vol. IA-23, no. 4, pp. 581-585, July/August 1987.

[14] A. L. Day and A. A. Mahmoud, "Methods of evaluation of harmonic levels in industrial plant distribution system" IEEE Transaction on Industrial Application, Vol. IA-23,No. 3, pp. 498-503.2, Dec. 1987.

[15] D. A. Gonzalez and J. C. McCall, "Design of filters to reduce harmonic Distortion in industrial power systems," IEEE Transaction Industrial Application., Vol. IA-23, no. 3, pp. 504-511, June 1987.

[16] Thomas A. Lipo, "Recent progress AC motor in the development of Solid-State Drives", IEEE Transactions on Power Electronics, Vol. 3, no. 2, pp. 105-117, April 1988.

[17] D.Finney, 1988, "Variable Frequency AC Motor Drive System", IEE Power Engineering Series 8, Peter Peregrinus Ltd.

[18] J. A. Oliver and B. B. Banerjee, "Power measurement and harmonic analysis of large adjustable speed drives," IEEE Trans. Energy Conversion, vol. 3, no. 2, pp. 384-390, June 1988.

[19] Robert A. Hanna, "Harmonics and technical barriers in Adjustable Speed Drives", IEEE Transactions on Industry Applications, Vol. 25, no. 5, pp. 894-900, September/October 1989.

[20] Paresh C. Sen, "Electric motor drives and control-past, present, and future", IEEE Transactions on Industrial Electronics, Vol. 37, no. 6, pp. 562-575, December 1990.

[21] Lament P., M. Gabsi, B. Multon, "Sensorless Rotor Position Detection using Resonant Method for Switched Reluctance Motors", IEEE IAS Annual Meeting, pp.687-694, 1990.

[22] F A. De Winter and L. G. Grainger, "A practical approach to solving large drive harmonic problems at the design stage," IEEE Transaction on Industrial Application, Vol. 26, Sept./Oct. 1990.

[23] H. Lee and R. H. Lee, "Origin & characteristics of harmonic currents-Part l," Power Quality, pp. 349-351, 1990.

[24] King, R. D., "HETX-II 70 Hp electric drive system performance-component tests," Proc. 10th Int. Elec. Vehicle Symposium, pp. 878-887, 1990.

[25] Jahns, T., "Designing intelligent muscle into industrial motion control," IEEE Transaction Industrial Electronics, Vol. 37, no. 5, pp. 329-340, October 1990.

[26] Jon W. Simons and Daniel A. Dey, "Use of functional descriptions in specifying Drive systems" IEEE Transactions on Industry Applications, Vol. 21, no. 1, pp., January/february 1991.

[27] F. A. DeWinter and L. M. Benke, "Systems engineering for large induction motor adjustable frequency drives," presented at the IEEE Petroleum and Chemical Industry Technical Conf., 1991.

[28] G. Carrara, S. Gardella, M. Marchesoni, R. Salutari, and G. Sciutto, "A new multilevel PWMmethod: A theoretical analysis," IEEE Trans. Power Electron., vol. 7, no. 3, pp. 497–505, Jul. 1992.

[29] Ehsani M., I. Husain, A.B. Kulkami, "Elimination of Discrete Position Sensor and Current Sensor in Switched Reluctance Motor Drives", IEEE Trans. on Industry Applications, Vo1.28, No. 1, pp 128-135, January/February, 1992.

[30] J. Holtz, "Pulsewidth modulation for electronic power conversion," Proc.IEEE, vol. 82, no. 8, pp. 1194–1214, Aug. 1994.

[31] Ehsani M., LHusain, S.Mahajan, K.RRamani, "New Modulation Encoding Technique for Indirect Rotor Position Sensing in Switched Reluctance Motors", IEEE Transactions on Industry Applications, Vo1.30, No. 1, pp.584-588,Jan/Feb. 1994.

[32] IEEE Std.519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems".

[33] J.Holtz, "Pulsewidth modulation for electronic power conversion," Proc. of IEEE, vol. 82, no. 8, pp. 1194-1213, 1994.

[34] W. Leonhard, "Controlled AC drives, a successful transition from ideas to industrial practice", Controleng. Practice, Vol. 4, no. 7, pp. 897-908, 1996.

[35] P. Y. Keskar, "Specification of variable frequency drive systems to meet the New IEEE 519 Standard", IEEE Transactions on Industry Applications, Vol. 32, no. 2, pp. 393-402, March/April 1996.

[36] James Will Gray and Frank J. Haydock, "Industrial power quality considerations installing Adjustable Speed Drive Systems", IEEE Transactions on Industry Applications, Vol. 32, no. 3, pp. 646-652, May/June 1996.

[37] Chris French and Paul Acarnley, "Direct Torque Control of Permanent Magnet Drives", IEEE Transactions on Industry Applications, Vol. 32, No. 5, pp 1080-1088, September/October 1996.

[38] Peter w. Hammond, "A new approach to enhance power quality for medium voltage AC drives", IEEE Transactions on Industry Applications, Vol. 33, no. 1, pp. 202-208, January/February 1997.

[39] Manufacturers' Experiences", IEEE Transactions on Industry Applications, Vol. 33, no. 6, pp. 1407-1415, November/December 1997.

[40] IEEE Std. 499-1997 (Revision of IEEE Std 499-1989), "IEEE Recommended Practice for Cement Plant Electric Drives and Related Electrical Equipment."

[41] Suresh G., B. Fahimi, M. Ehsani, "Improvement of the Accuracy and Speed Range in Sensorless Control of Switched Reluctance Motors", IEEE APEC Conference Records, pp.770-777, 1998.

[42] A. Mertens, M. Bruckmann, and R. Sommer, "Medium voltage inverter using high-voltage IGBTs," in Proc. EPE Conf. Rec., Lausanne, Switzerland, 1999.

[43] Cristian Lascu, Ion Boldea and Frede Blaabjerg, "A Modified Direct Torque Control for Induction Motor Sensorless Drive", IEEE Transactions on Industry Applications, Vol. 36, No. 1, pp. 122-130,January/February 2000.

[44] S. Bernert, "Recent developments of high power converters for industry and traction applications," IEEE Trans. Power Electron., vol. 15, no. 6, pp. 1102–1117, Nov. 2000.

[45] Thomas M. Jahns and Edward L. Owen, "AC Adjustable-Speed Drives at the Millennium: How Did We Get Here?", IEEE Transactions on Power Electronics, Vol. 16, no. 1, pp. 17-25, January 2001.

[46] Sidney Bell, Timothy J. Cookson, Steven A. Cope, Richard A. Epperly, Annika Fischer, David W. Schlegel and Gary L. Skibinski, "Experience With Variable-Frequency Drives and Motor Bearing Reliability", IEEE Transactions on Industry Applications, Vol. 37, no. 5, pp. 1438-1446, September/October 2001.

[47] Cao-Minh Ta, Member and Yoichi Hori, Convergence Improvement of Efficiency-Optimization Control of Induction Motor Drives", IEEE Transactions on Industry Applications, Vol. 37, No. 6, pp. 1746-1753, November/December 2001.

[48] Alessandro F. Moreira, Thomas A. Lipo, Giri Venkataramanan, and Steffen Bernet, "High-Frequency Modeling for Cable and Induction Motor Overvoltage Studies in Long Cable Drives", IEEE Transactions on Industry Applications, Vol. 38, no. 5,pp. 1297-1306, September/October 2002.

[49] M. Jones, and E. Levi, "A literature survey of state-of-the art in multiphase ac drives," in 2002 Proc. Universities Power Eng. Conf, pp.505-510.

[50] R. Bojoi, A. Tenconi, F. Profumo, G. Griva, and D. Martinello, "Complete analysis and comparative study of digital modulation techniques for dual three-phase AC motor drives", in 2002 Proc. IEEE PESC Conf, pp. 851-857.

[51] J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls and applications," IEEE Trans. Ind. Electron., vol. 49, no. 4, pp. 724–738, Aug. 2002.

[52] F. Naceri and L. Abida, "A novel robust adaptive control algorithm for AC drives", Computers and Electrical Engineering 29(2003), pp. 523–534, 2003.

[53] R. Champagne, L.-A. Dessaint and H. Fortin-Blanchette, "Real-time simulation of electric drives", Mathematics and Computers in Simulation 63 (2003), pp. 173–181, 2003.

[54] N. Zargari and S. Rizzo, "Medium voltage drives in industrial applications," in Proc. Tech. Seminar, IEEE Toronto Section, Nov. 2004.

[55] Aníbal T. de Almeida, Fernando J. T. E. Ferreira and Dick Both, "Technical and Economical Considerations in the Application of Variable-Speed Drives With Electric Motor Systems", IEEE Transactions on Industry Applications, Vol. 41, no. 1, pp. 188-199, January/February 2005.

[56] IEEE Std. 1566-2005, "IEEE Standard for Performance of Adjustable Speed AC Drives Rated 375 kW and larger."

[57] L. Szentirmai and T. Szarka, "Electrical Engineering and Drives in the Globalization Age and Their Contribution to Sustainable Development and Knowledge-based Society", SPEEDAM 2006 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, S31-1 -6, 2006.

[58] Kyo-Beum Lee, and Frede Blaabjerg, "Improved Sensorless Vector Control for Induction Motor Drives Fed by a Matrix Converter Using Nonlinear Modeling and Disturbance Observer", IEEE Transactions on Energy Conversion, Vol. 21, pp. 52-59, No. 1, March 2006.

[59] S. Bernet, "State of the art and developments of medium voltage converters—An overview," Prz. Elektrotech. (Electrical Review), vol. 82, no. 5, pp. 1–10, May 2006.

[60] T.N. Date and B.E. Kushare, "Evaluation of performance of AC drive under unbalanced voltage conditions and AC line reactor harmonic mitigation performance at various loading conditions", IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES 2007), pp.308-314Dec. 20-22, 2007.

[61] Cursino Brandão Jacobina, Euzeli Cipriano dos Santos, Maurício Beltrão de Rossiter Corrêa, and Edison Roberto Cabral da Silva, "AC Motor Drives With a Reduced Number of Switches and Boost Inductors", IEEE Transactions on Industry Applications, Vol. 43, no. 1, pp. 30-39, January/February 2007.

[62] José Rodríguez, Steffen Bernet, BinWu, Jorge O. Pontt, and Samir Kouro, "Multilevel Voltage-Source-Converter Topologies for Industrial Medium-Voltage Drives", IEEE Transactions on Industrial Electronics, Vol. 54, no. 6, pp. 2930-2945, December 2007.

[63] Marc Hiller, Rainer Sommer and Max Beuermann "Medium voltage-drives", IEEE Industry applications magazine, pp. 22-30, Mar./Apr. 2010.

[64] Joseph Song-Manguelle, Stefan Schröder, Tobias Geyer, Gabriel Ekemb and Jean-Maurice Nyobe-Yome, "Prediction of Mechanical Shaft Failures due to Pulsating Torques of Variable Frequency Drives", IEEE Transactions on Industry Applications, Vol. 46, no. 5, pp. 1979-1988, Sept./Oct., 2010.

[65] Ehsani M., "Position Sensor Elimination Technique for the Switched Reluctance Motor Drive", US Patent 5072166.

[66] Technical literature, Siemens.G. Eason, B. Noble, and I. N. Sneddon, "On certain integrals of Lipschitz-Hankel type involving products of Bessel functions," Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955.

AUTHORS PROFILE

Mrs. Anuradha Tomar Chauhan, received her B.E degree in Electronics Instrumentation & Control Engineering with "Honours" from Institute of Engineering. & Technology, Alwar (Raj) in 2007. & M.Tech, Power System, National Institute of Technology, Hamirpur (H.P.) and Ph.D degree from Singhania Univerity. Currently working as Assistant Professor in Northern India Engineering College. She is member of IEEE, IAENGG, IAEMA etc. and published many research papers in various reputed journals. Her areas of interest are Electrical drives, Wireless power transmission, Automation.

Mr. Devesh Singh Tomar, received his B.Tech degree in Electrical Engineering with "Honours" from Indian Institute of Technology (I.I.T, Roorkee), in 1976. He has More than 17 years experience in H.M.T. Ltd. as Design Head and Assistant General Manager. These days he is associated with "Prabha Electronics Automation", Ajmer (Raj.). His areas of interest are Automation, A.C. Drives, CNC Systems and PLC.

Dr. Yog Raj Sood received his B.E. degree in Electrical Engineering with "Honours" and M.E. in Power System from Punjab Engineering College Chandigarh (U.T.), in 1984 and 1987 respectively. He has obtained his Ph.D. from Indian Institute of Technology, Roorkee in 2003. He joined TIET Patiala in January 1986 and NIT Kurukshetra in July 1986. Presently he is Professor (Electrical Engineering) & Dean (Research and consultancy) at National Institute of Technology, Hamirpur. He has published a number of research papers (more than 180). He has been honored with many awards and appreciation letters for his excellence administrative, academic and research.