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1983 THIRTY-FIFTH ANNUAL CONFERENCE OF ELECTRICAL ENGINEERING PROBLEMS IN THE RUBBER AND PLASTICS INDUSTRIES

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THIRTY-FIVE YEARS WITH THE RUBBER AND PLASTICS COMMITTEE

Newell A. Williams
Goodyear Tire And Rubber Company (Retired

Ten years ago, Tony Seifried and I presented a paper on the history of this committee and conference. Since that time we have both retired, Tony from Goodrich, and I from Goodyear. If this paper sounds familiar it is because a large part is copied from that paper. In the last thirty-five years there have been thirty-four conferences, such as this, held in or near Akron. I have attended all except two. In both cases, I was out of the country on business. This record is surpassed only by my good friend Ed Buess (Ex. G.E. Co.). I believe that Ed has a perfect record, having been at all thirty-four.

One of the first attempts to coordinate electrical motor drive requirements of the Rubber Industry with an AIEE technical meeting was held by the Akron-Cleveland Section, at the B.F. Goodrich Company, on January 14, 1921. A report of the meeting, made by the Subcommittee of the Rubber Industry Power Committee, revealed many electrical differences of that time as compared to today. For example, a #3 rubber mixer with 70 lbs. of crude rubber required an average of 50 HP. Safety stops on Mills were made by disconnecting the motor and applying a brake to the load. The report mentioned that plugging the motor had been tried but was unsuccessful. The report did not mention dynamic braking.

Up until the year 1947, the growing AIEE Committee on General Industry Applications held annual conferences and presented technical papers on electrical engineering problems in a wide range of industries. At that time, Mr. L.A. Umansky, of General Electric Company, and chairman of the AIEE Committee on General Industry Applications, suggested that more benefits could be derived to industry and the electrical engineering profession if individual groups were formed in each specialized industry. A subcommittee on Rubber and Plastics Industries was formed and members appointed. The first meeting was held in Dayton, Ohio, in September, 1947. At this meeting it was decided to:

1. Initiate the writing of technical papers dealing with problems of power utilization in the Rubber and Plastics Industries.
2. Help organize programs for engineering sessions at National or district meetings for the presentation of the papers.
3. Stimulate development of electrical engineering standards and recommended practices in our industries.

The first conference took place April 20, 1948 and was held in the auditorium of O'Neils Department Store. The attendance was 134. My main recollection was that it was very hot and uncomfortable in the room. Our committee was then known as AIEE Subcommittee on Rubber and Plastics Industries. Its chairman was Kirt W. John of United States Rubber Co. (now Uniroyal). Other members were: A.T. Bacheler - Westinghouse, Paul Bechtol - Goodrich, B.J. Dalton - General Electric, J.A. Grenger - Kodak, V.O. Johnson - U.S. Rubber, G.V. Kullgren - Adamson United, B.D. Morgan - Johnson & Johnson, Bill Secrest - Firestone, H.L. Smith - General Electric, and Bob Snyder - Goodyear.

And as Mr. Umansky stated during the first Rubber and Plastics Conference meeting in 1948:

"There is no better way to further engineering knowledge than to bring together a group of engineers with wide and varied experiences and to spend a day in a free interchange of ideas and facts. Let us hope that this meeting being the first of its kind in the rubber industry, will not be the last."

"It takes about 2300 KW hours for each ton of rubber processed in your plants. This can be compared with about 200 KW hours per ton of steel, or 700 KW hours for each ton of paper."

There were papers on Power Distribution in Rubber Plants, Adjustable Speed Drives, Control Rooms versus NEMA Enclosures, Electrical Braking of Mills and Calenders, and Measurement and Control of Tension and etc. relation to motor input. Any one of these papers is still pertinent and can be read now with profit to the rubber electrical engineer today.

After the conference, a decision was reached to make the conference program an annual affair, to be held in Akron, due to its favorable position in the center of the rubber industry.

The technical papers, presented at the Conference, together with prepared and extemporaneous discussions, were printed into a booklet form and sold to AIEE members and non-members for future references. These procedures laid the ground-work and foundation for building successful and badly needed engineering cooperation, which has proven to be of high value to all Rubber and Plastics manufacturing plants.

It was decided at this time, to ask each chairman to serve two consecutive years.

The second years conference was held April 26, 1949 at the Portage Hotel. I would not presume to select the most important paper given in the twenty-five years of our existance, but one of the top five was given at our second meeting. It was "Motor Requirements for Rubber Mill Drives" by R.S. Ferguson. It is still used in our department as a reference and is recommended to our new engineers. In addition, there were several papers on JIC Standards.

In 1950 the conference was again held in the Portage Hotel. Its chairman was R.F. Snyder. In the proceedings at this conference, we find more papers on electronics. Tension control in calender windups, and industrial communication systems were covered. There was also a paper on the safety code for mills and calenders.

There was no conference in 1951 due to the Korean War. Then in 1952 the conference was again held in the Portage Hotel. Electronic control was the main topic with papers on calender control, mercury arc rectifiers, magnetic amplifiers and beta gauge applications.

In 1953 and 1954 the subjects of power distribution and large motors for mills and banburys were again covered. Of special interest were the new insulation systems then being developed for medium voltage motors. In 1954 the conference became a two day affair and 229 persons attended.

The 1955 conference produced another of our top five papers "Comparison of Rotating, Electronic, and Magnetic Amplifier Regulators" by J.P. Montgomery of Westinghouse. At this time the committee organized a special study group to study problems due to atmospheric contamination under the chairmanship of Ed Smith of Firestone.

There can be no doubt that this group was one of the most important activities of our committee. Through its activity we were able to make large motor manufacturers face up to the problem of lamp black contamination and its effect on motor windings. New motor test standards were established, and new cleaning methods introduced.

During the four years this group was active, it visited plants of most of the large motor manufacturers, and discussed "the lamp black problem" with their motor designers. By 1960, improved insulation systems were being offered by all suppliers. Certainly our committee can be proud of its part in this development.

Another activity started at this time was the writing of the medium voltage controller standards. This group was under the leadership of Bill Watkins, then of the Ohio Rubber Co. Bill was able after many frustrations, to get this proposal adopted by AIEE Standards Committee as a Recommended Practice. It is still used by several large rubber companies as a basis for their own specifications.

In 1959 our conference was held in conjunction with the East Central District meeting of the AIEE. It was a three day affair and had a total attendance of 700. In the 1960's the conference returned to the two day format. The subjects covered reflect the rapid advances being made in the electrical industry. In 1959, mention was made of static switching. In 1960 the first paper on computer programming was given, and in 1961, SCR regulators were covered.

In 1961 we had a paper by P.E. Purcell of English Electric Co. on British Electrical Engineering Practices. In 1962 there were two more papers by an English engineer on process control systems as designed by British companies. Several papers appeared in the next two years on process control computers. We also find discussions on SCR power rectifiers and how to best protect them.

Static logic and digital control systems were covered in 1965 and 1966. There was also much interest shown in new instrumentation techniques and sensors. While the program did not overlook rubber processing machines and electric power distribution problems, it was evident that the interest of the rubber electrical engineers was in what was new.

It is interesting to note, that the birth of our committee and the invention of solid state electronics occurred in the same year. In 1948 the only electronic devices we had was the vacuum tube, and the thyration. Goodyear had used the thyration for conveyor synchronization for several years. In 1947 U.S. Rubber installed a four roll calender with individual motor driven auxiliaries synchronized by electronic controls. I can remember feeling jealous of their engineers. However my turn soon came. In 1948 Goodyear decided to put in what we then called "Our first modern calender train". It was a four roll "Z" type with individual driven auxiliaries. I was responsible for writing the electrical drive specification. Its installation was under the supervision of my best friend Jack Hall (another member of the Rubber and Plastics Committee for many years). We were very proud of this installation, and Jack presented a paper on it at our 1952 conference. It used rotating regulators for drive synchronizing. (I'll bet some of you younger engineers don't even know what a rotating regulator is). This machine was scrapped last year. I was saddened when I read about it. It was almost like losing one of your children.

It was on this calender that we installed our first "Beta-Ray Gauge". The original gauges were magnetic type on the rolls and capacitor type to measure the overall thickness. Needless to say, they left a lot to be desired. But enough of the reminiscences of an old man.

In 1961 the committee achieved full committee status in the AIEE. Then in 1963 the old AIEE combined with I.R.E. to become the IEEE. Our committee became the Rubber and Plastics Committee of the Industry and General Applications Group. Later called the Industry Application Society. We are now one of more than 20 committees in that society. Since 1966 we have also sponsored a session at the Fall General Meeting of the I.A.S.

In conclusion let me paraphrase the words of our founder, Mr. L.A. Umansky, "Let us hope that this meeting being the 34th of its kind in the rubber industry, will be far from the last".

VACUUM CONTACTORS

THEIR APPLICATION AND ADVANTAGES

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INTRODUCTION

Vacuum motor control gear has been in use in a variety of industrial plants for many years and offers certain advantages over more established air break motor starters. These advantages of space savings, reduced maintenance, lower losses, quiet operation and resistance to atmospheric pollution are explained and related to specific equipment designs.

DESIGN CONSTRAINTS

The 5 KV motor control gear and transformer feeders used in process plants should be designed to suit the arduous operating conditions encountered. Regular maintenance for instance should be reduced to an absolute minimum and the consequences of the maintenance not being performed at all for extended periods should be non-catastrophic for the equipment and always safe for the operating persons.

Many plants now install closed circuit air conditioning to reduce damage to electrical equipment and if necessary air filters are being used to remove dust and gaseous contamination from the equipment room. However, even with these steps to clear up the atmosphere, contamination of air is possible and electrical equipment should be designed to be as resistant as possible to these hostile elements.

Vacuum motor control which is of relatively modern design provides protection from the environment in two ways. Firstly, it offers as complete a phase to phase and phase to ground segregation as possible and the use of bolted connections where appropriate. Secondly, it operates with the electrical contacts of the contactor in a vacuum, thus removing the possibility of atmospheric contamination of those contacts. These subjects are more throughly explored later.

VACUUM SWITCHING

The operation of interrupting current using a vacuum was first put into industrial apparatus some twenty years ago and is now well proven. A vacuum switch should not only have the ability to hold a vacuum indefinitely but also have some particular electrical characteristics. The most important of these are good hard contacts so that wear rates are very low, and contact material which minimizes voltage transients during the switching operation. These two requirements tend to be mutually exclusive in one single metal so vacuum switches used for vacuum contactors will invariably have at least two metals in the switch contact areas; one hard material to carry current with low wear and low contact resistance and a second metal to act while the switch is being opened. This second metal ionises as the switch is opened and carries the load current until it has decayed to well under 1 amp. At this low level, the current can be interrupted without harmful voltage disturbances. The point at which current is extinguished is commonly referred to as the current chop level of the vacuum switch and this level is determined by the material used in the contacts.

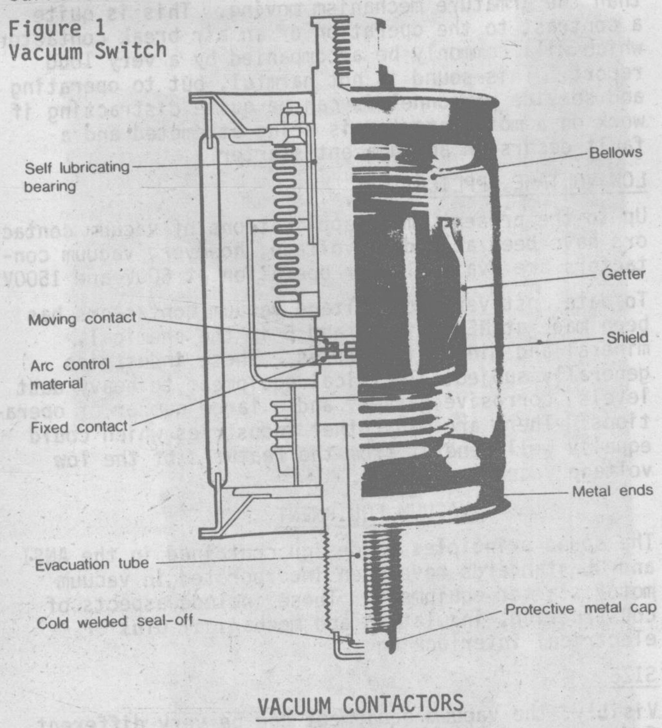
Figure 1 shows an arrangement of two metals which produces good results. Main current is carried by tungsten and opening current is carried by a metal mixture of antimony busmuth. Both contacts have the same metal configuration.

The carefully chosen metal contacts are enclosed in a glass envelope which has bellows at one end to allow the switch to operate. The whole of the switch is made resistant to the corrosive chemicals found in industrial environments. Stainless steel bellows with a stringent metalurgical specification are chosen so that the switch will be resistant to chlorine stress cracking.

The vacuum switch is therefore a very carefully engineered product which is extremely reliable and has an exceptionally long life. An incidental advantage of the switch is that the operation of the device, even under fault conditions, is very quiet.

Also these switches will operate equally well at high or low current. The switch shown will interrupt currents between, say, 5 amps and 8KA and is 3¼ inches in diameter. It is worth noting that some air break contactors would have difficulty operating within this range of current because the blow out coils and arc chutes are designed for specific current levels.

Figure 1
Vacuum Switch



VACUUM CONTACTORS

Electrical contactors with a NEMA E2 rating are designed to be operated a large number of times and have a coordinated current limiting fuse. Such contactors must be clearly separated from the NEMA E1 unfused breaker devices commonly used for infrequent but very harsh duty. This separation is particularly important in vacuum technology because vacuum switches designed for E2 duties produce only minimal voltage transients whereas vacuum bottles designed for E1 duties may produce voltage transients and need surge arrestors to be fitted, the latter being the wrong device for motor control.

The vacuum switch used in a vacuum contactor is designed to be operated a large number of times, say, two million mechanical operations or one million operations at maximum rated current. Typically a wear check should be made every half million operations. It will also produce a minimum of voltage disturbance as it operates, a voltage disturbance comparable with many air break contactors.

As all the action of current extinction is held within the vacuum switch there is no need for arc chutes or blow out coils and without these two items, the design of the vacuum contactor can be manipulated to suit equipment requirements. Two common shapes for the vacuum contactor are shown in Fig. 2. First, a cubic arrangement for minimum contactor volume and second, a slimline arrangement for use where plan area in an equipment is limited. This slimline contactor incorporated into a motor control apparatus can produce a very compact design.

A comparison of the vacuum contactor with an air break device reveals that the vacuum contactor has considerable less volume, absence of blow out coils and lower hold in power requirements. These factors combine to offer the user lower power losses with the vacuum device.

As a component, the vacuum contactor is quiet. If a vacuum contactor is called to operate at maximum interrupt current, all that is heard is little more than the armature mechanism moving. This is quite a contrast to the operation of an air break contactor which will commonly be accompanied by a very loud report. This sound is not harmful, but to operating and service personnel is can be quite distracting if work on a motor starter is being attempted and a fault occurs in an adjacent starter.

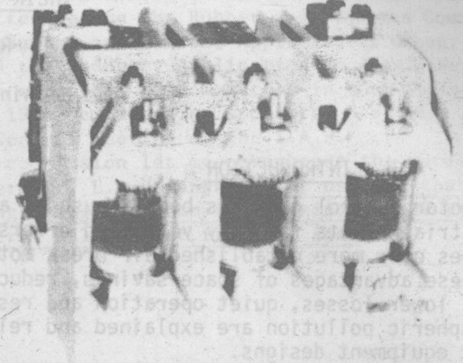


Fig. 2(a)

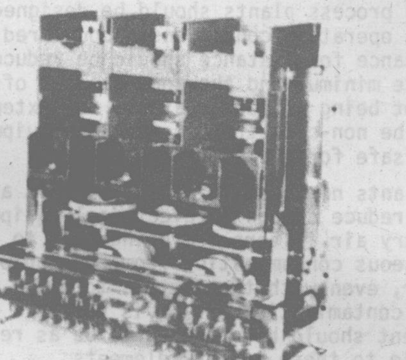


Fig. 2(b)

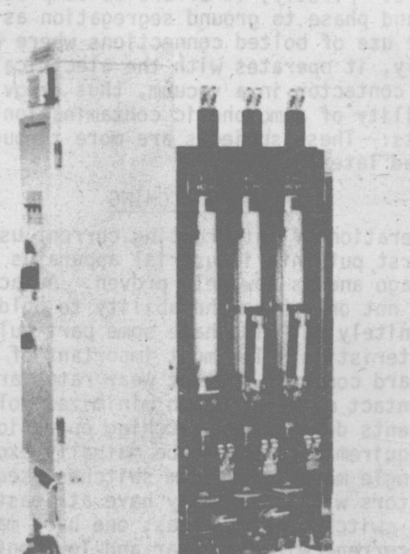


Fig. 3
Motor Starter Truck

LOW VOLTAGE APPLICATIONS

Up to the present, most applications of vacuum contactors have been at medium voltage; however, vacuum contactors are available for operation at 600V and 1500V.

To date most very low voltage vacuum contactors has been made at NEMA size 4 and 5 in the chemical, mineral and mining industries. These industries generally subject electrical equipment to heavy dust levels, corrosive gasses, and a large number of operations. There are many other industries which could equally well benefit from the features of the low voltage vacuum contactor.

VACUUM EQUIPMENT

The sound principles of design contained in the ANSI and UL standards have been incorporated in vacuum motor starter equipment. These include aspects of construction, insulation and mechanical plus electrical interlocking.

SIZE

Visibly, the vacuum equipment can be very different from the more conventional air break apparatus. This difference arises because the vacuum contactor can be shaped to suit the apparatus requirements. See Fig. 3 which shows a vacuum contactor built into a removable starter unit. A group of three such starter units assembled into equipment is illustrated in Fig. 4 In this example, single tier equipment can be constructed with a total single starter width of 12.75 inches. It is worth contrasting this single tier equipment rated at 7.2KV with an earlier three-high arrangement (Fig. 5). Not only does the single tier equipment allow more units per square footage but it also permits easy cable access (both low voltage and medium voltage) into both top and bottom of the equipment and allows all connections to be made at the very front of the equipment. Using this arrangement, it is always possible to isolate one starter and work on it without affecting any other circuit. Problems associated with pulling new cables through one starter into the next are present in all multi-tier equipments but can be eliminated by the use of single tier designs.

BOLTED CONNECTIONS

The fuses in the vacuum equipment shown are bolted in place. This is a deliberate action to reduce energy dissipation and eliminate the occasional equipment failures due to atmospheric contamination producing high resistance connections on ferrule mounted fuses. Spring loaded disconnects should only be used where absolutely essential in making the contactor removable. Standard R type fuses can be converted from ferrule to tag mounting by means of a simple adaptor.

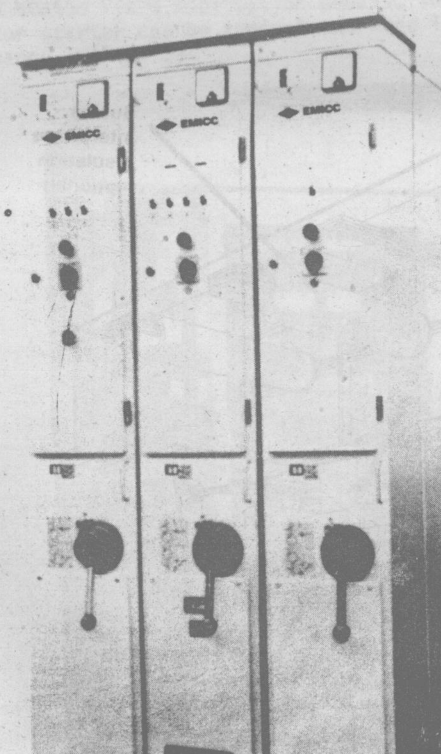


Fig. 4 Single Tier Motor Starters

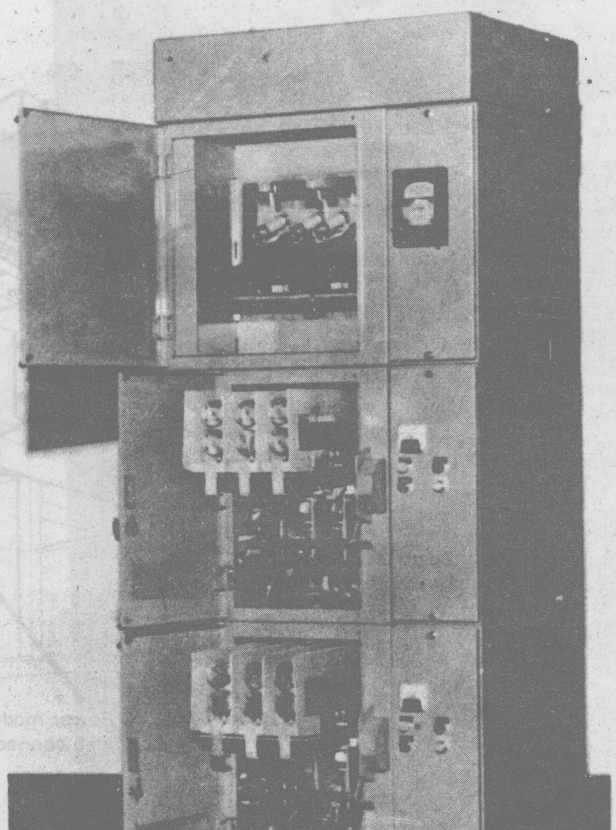


Fig. 5 Multi Tier Motor Starters

PHASE SEGREGATION

It is most important that the removable contactor unit be provided with both phase to phase plus phase to ground separators and that adequate barriers are installed to prevent a fault propogating through a switchboard. The illustration Fig. 6 shows the segregation panels and also the barrier between the stabs and the busbars.

BUS BARS

Fig. 6 also illustrates how the bus bars between the main bus and individual starters have been eliminated with associated reduction in heat generation (and equipment cost). As in the rest of the starter, it is important to be able to prevent phase to phase faults on the bus bars propogating out of one starter and along the board. Barriers to such propagation are clearly shown in this illustration.

Special care should be taken to select the type of bus bar plating, either silver or tin, to suit the particular industry conditions. Extra attention should be given to tin plated finger/stab assemblies where surfaces should be coated with a suitable lubricant to ensure long life.

SAFETY

Complete mechanical and electrical interlocking is achieved in the design shown. This is essential to prevent incorrect withdrawal of the power module.

Grounded metal is placed between the control devices and the medium voltage equipment to give greater operator safety. Similarly, a grounded metal shutter automatically covers the line side connection as the contactor is withdrawn.

The contactor is designed in a way that loss of vacuum will prevent the armature from operating. This is achieved simply because all three vacuum switches need to be sound in order to provide enough closing force for the contactor.

Loss of vacuum is a condition which has seldom if ever been encountered on site but one which must be fully considered in the mechanical design of the contactor.

A "fault make grounding" switch can be incorporated in the starter to ensure safe working on the load side of the starter.

MULTIPLE CONTACTORS

The application of a compact vacuum starter to any one of the numerous reduced voltage configurations or to motors with special winding arrangements highlights the space savings available. To illustrate this aspect of vacuum technology, the following are

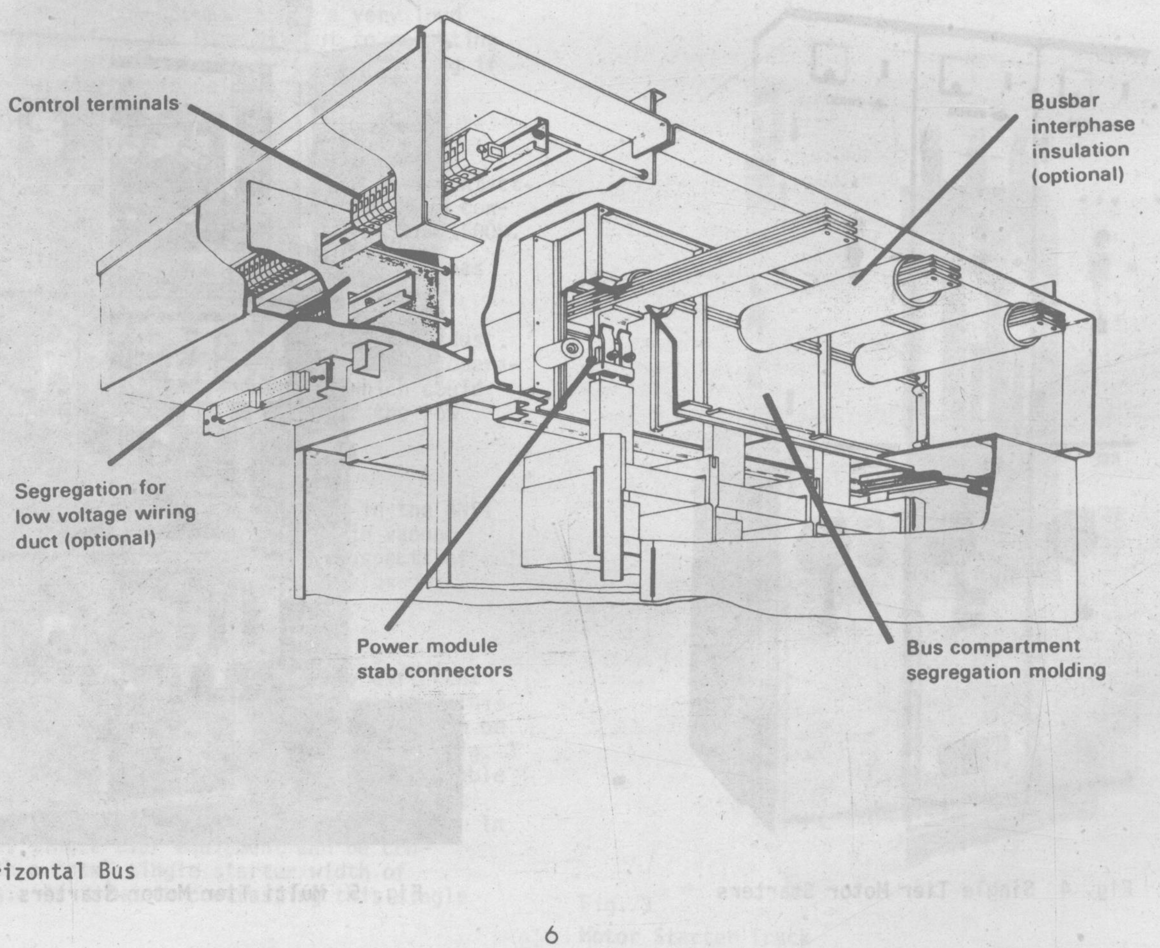


Fig. 6 Horizontal Bus

are very common arrangements:

a. An auto transformer starter (Fig. 7) produces reduced voltage starting of an induction motor. The unit illustrated is just three feet wide, has a withdrawable main contactor and two auxiliary contactors used to achieve a closed transition start. These contactors slide out for access. Room is also provided in the package to start up to 900 hp motor. With the addition of an extra foot in width, the rating can be raised to 1750 hp. The equivalent air break device would be as much as twice the width.

b. A wound motor starter used to provide a soft start on an induction motor. The low voltage motor contactors are mounted in the left hand cubicle of Fig. 7 in place of the medium voltage vacuum contactors.

c. A two winding motor starter can be constructed in just two feet width. Both contactors are mounted on the withdrawable power unit and are connected to the motor via output shutters.

d. A reversing or plug stop motor controller can be made in two feet width. Both contactors are on the same power frame with mechanical and electrical interlocking between contactors. (Fig. 8).

SYNCHRONOUS MOTOR STARTERS

Energy efficient industries have long been aware of the savings that can be obtained from the use of synchronous motors on such applications as compressors, blowers and pumps. Although efficient, synchronous motors need considerably more control apparatus to be used to ensure full protection and accurate control over power factor. With the use of vacuum contactors and static field application panels, the synchronous motor starter can be compact and need little maintenance. (Fig. 9).

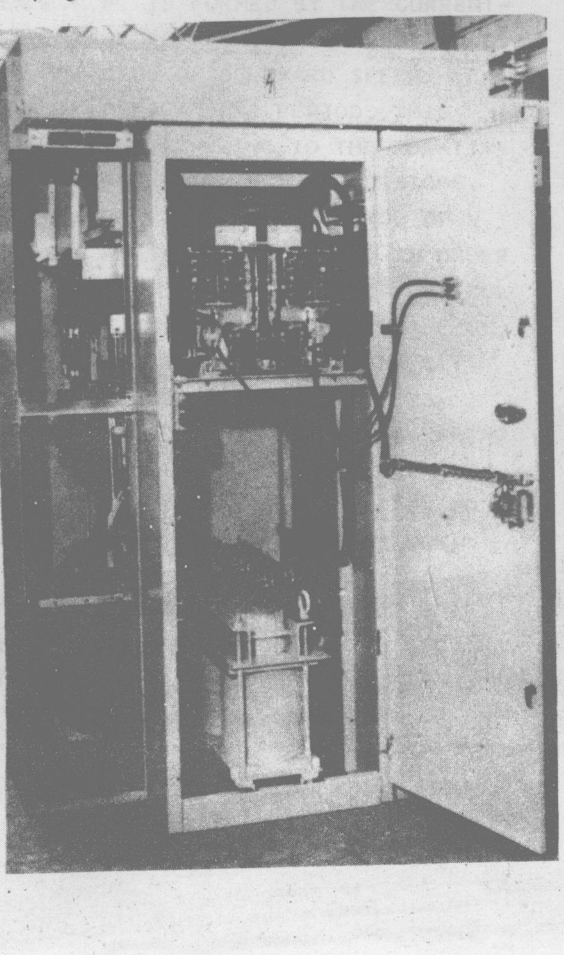


Fig. 7

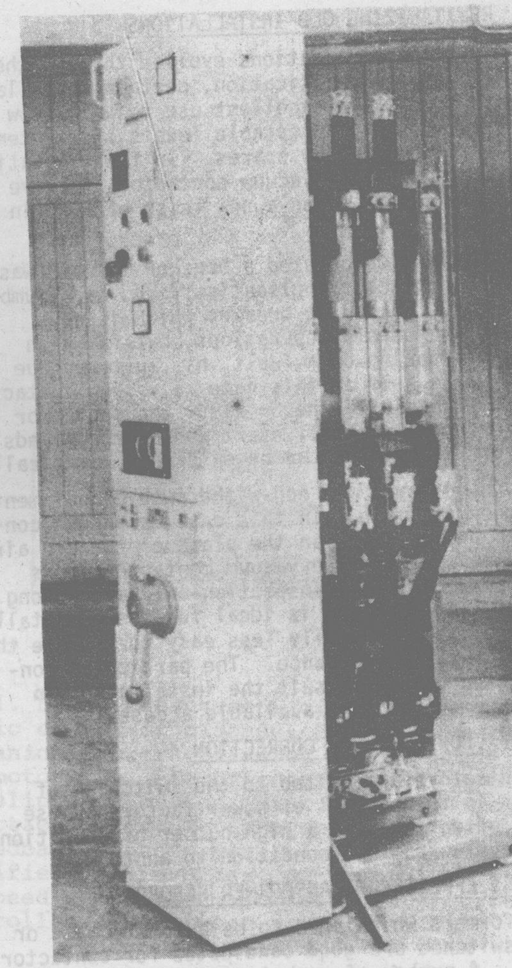


Fig. 8 Reversing Starter Truck

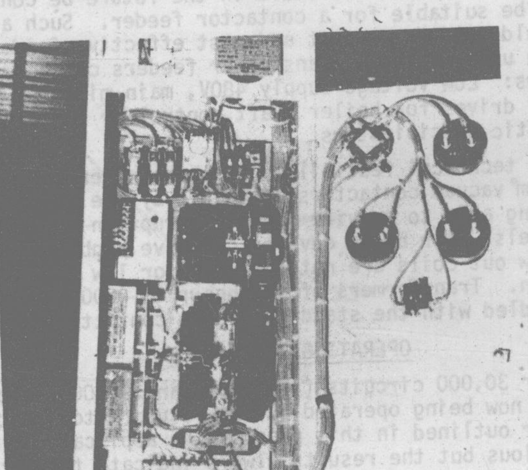


Fig 9 Typical Static Field Control For Synchronous Motor

REVITALIZING OLD INSTALLATIONS

As medium voltage applications evolved through their various levels of sophistication, certain installations which have given excellent use to date, now need more than merely acceptable levels of maintenance and are very expensive on spares. In this situation it is possible, using a vacuum contactor, to give the existing installations a new lease of life in one of two ways:

For installations which used a breaker in what was rightfully a contactor application (i.e. high number of operations). Here the breaker which is not designed for numbers of operations, but for high integrity of opening on a fault, has suffered due to excessive usage. If in this case, a vacuum contactor is used in series with the breaker, the contactor opening for normal control start and stop commands, the life of the breaker can be extended dramatically.

Secondly, consider early non-withdrawable equipment needing modernization. In this case, a vacuum contactor can be installed in the place of the old air or oil break switch. The vacuum contactor needs regular maintenance and inspection only after long periods of operation and is ideal for these installations where it is generally less easy to isolate the power device for maintenance. The particular contactor can be chosen to suit the installation in both arrangement and the available access.

POWER FACTOR CORRECTION

Vacuum contactors are suited to the switching of capacitors in the control of power factor because this duty often involves a high number of operations as loads cycle from one condition to another.

COST EFFECTIVE TRANSFORMER FEEDER

All transformers which need to be automatically or remotely switched are good candidates for contactor equipment. A number of such transformers are now fed by breakers and could in the future be considered to be suitable for a contactor feeder. Such a move would produce compact and cost effective feeders. The uses of these transformer feeders can be as follows: Low voltage supply 480V, main mill SCR drives, SCR drives for boiler draft control or for electrostatic precipitators.

The technical feasibility of transformer feeders from vacuum contactors is helped by the vacuum devices being able to provide good interruption at low current levels. Air break devices can have problems if the blow out coils are not designed for low level operation. Transformers of ratingsup to 4000KVA can be handled with the standard vacuum contactor.

OPERATING EXPERIENCE

Over 30,000 circuits (incorporating 90,000 switches) are now being operated by the vacuum motor control gear outlined in this paper. The applications are various but the results always indicate the vacuum contactor to be very reliable.

CONCLUSION

Vacuum contactors applied correctly and incorporated into a total equipment which takes full advantage of the special features of the vacuum contactor can offer the following advantages over the more conventional air break contactors.

1. Necessary maintenance is reduced.
2. Installation and maintenance is made easier by single tier starter designs incorporating vacuum contactors which roll into place on their own wheels.
3. Floor area used by the equipment is minimized.
4. Energy losses are reduced.
5. Safety for maintenance personnel can be enhanced by using a modern equipment incorporating good mechanical and electrical design.
6. Greater resistance to atmospheric contamination by operating the main contacts in a vacuum.

SUBSYNCHRONOUS STATIC
CONVERTER CASCADES

1 MODE OF OPERATION

IN A SUBSYNCHRONOUS STATIC CONVERTER CASCADE, THE SPEED OF AN A.C. SLIPRING INDUCTION MOTOR CAN BE VARIED ALMOST LOSS-FREE BY MEANS OF A STATIC FREQUENCY CONVERTER - THIS COMPRISES AN UNCONTROLLED RECTIFIER AND A LINE-COMMUTATED INVERTER - ARRANGED IN THE ROTOR CIRCUIT (FIG.1).

THE SPEED OF AN A.C. INDUCTION MACHINE OPERATED ON AN A.C. SYSTEM OF CONSTANT VOLTAGE AND FREQUENCY CAN ONLY BE VARIED BY INJECTING A COUNTER E.M.F. INTO THE ROTOR CIRCUIT OF THE MOTOR. THIS VOLTAGE OPPOSES THE THE VOLTAGE INDUCED IN THE ROTOR WHOSE MAGNITUDE IS DEPENDENT ON THE SLIP, I.E. ON THE RELATIVE DEVIATION OF THE OPERATING SPEED FROM THE SYNCHRONOUS SPEED. STARTING FROM A MAXIMUM AT ZERO SPEED, THE RECTIFIED ROTOR VOLTAGE Ud DECREASES LINEARLY AS THE SPEED N INCREASES AND ATTAINS A VALUE OF ZERO AT SYNCHRONOUS SPEED. (FIG.2).

IF THE SPEED OF THE MOTOR IS CONTROLLED BY VARIABLE RESISTORS IN THE ROTOR CIRCUIT, THE COUNTER E.M.F. IS FORMED BY THE CURRENT-DEPENDENT VOLTAGE DROP ACROSS THE RESISTORS. HOWEVER, IN THE CASE OF DOWNWARD SPEED CONTROL LASTING OVER A LONG PERIOD, THIS METHOD IS UNECONOMICAL OWING TO THE RELATIVELY HIGH LOSSES OCCURING IN THE RESISTORS. IT MAY BE COMPARED WITH SPEED CONTROL OF D.C. MOTORS VIA ARMATURE RESISTORS. IN ORDER TO OBTAIN ECONOMICALLY OPTIMAL SPEED CONTROL FOR D.C. DRIVES, USE WAS PREVIOUSLY MADE OF WARD-LEONARD SETS, WHICH HAVE NOW LARGELY BEEN SUPERSEDED BY THYRISTOR CONVERTERS. DEVELOPMENT IN THE SPEED CONTROL OF SLIPRING MOTORS TOOK A SIMILAR COURSE WHICH LED FROM VARIABLE RESISTORS VIA MACHINE CASCADES TO SUBSYNCHRONOUS STATIC CONVERTER CASCADES.

IN THESE, THE ROTOR VOLTAGE AND ROTOR CURRENT ARE RECTIFIED BY AN UNCONTROLLED RECTIFIER N1 (FIG.2) AND A COUNTER E.M.F. IS GENERATED BY A CONVERTER N2 OPERATING AS AN INVERTER.

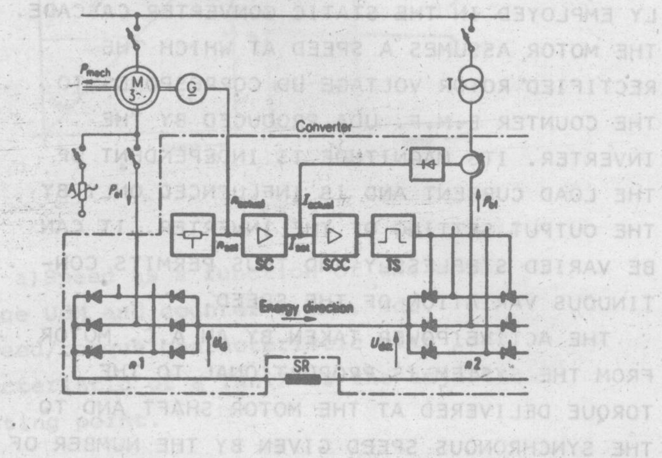


Fig.1. Basic arrangement of a subsynchronous static converter cascade. Symbols: Pmech-mechanical power delivered at the shaft of the motor, Pel-electric power collected at the sliprings of the motor, M-a.c.slipring induction motor, G-tachogenerator, A-starter, T-feedback transformer, n1-uncontrolled rectifier, n2-inverter; SR-smoothing reactor SC-speed controller, SCC-secondary current controller, TS-trigger set.

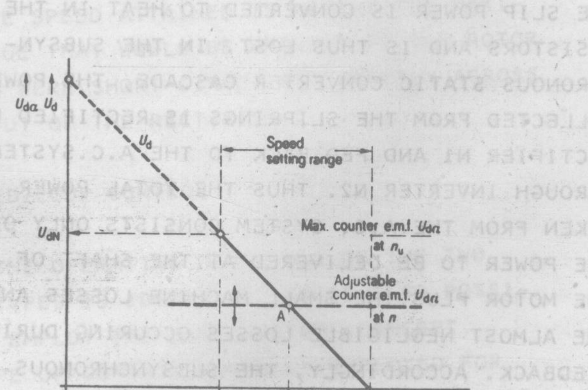


Fig.2. Voltages in the d.c.link of the converter with open-loop speed control. Symbols: Ud-rectified rotor voltage, Uda-adjustable counter e.m.f., UdN-rectified rotor voltage at lowest speed=rated voltage of converter, nu-lowest speed of setting range, n-adjustable operating speed,ns-synchronous speed.

THE ROTOR VOLTAGE AND THE DIRECT CURRENT HAVE A FIXED RELATIONSHIP WHICH IS DETERMINED BY THE THREEPHASE A.C. BRIDGE CIRCUIT NORMALLY EMPLOYED IN THE STATIC CONVERTER CASCADE. THE MOTOR ASSUMES A SPEED AT WHICH THE RECTIFIED ROTOR VOLTAGE UD CORRESPONDS TO THE COUNTER E.M.F. UDA PRODUCED BY THE INVERTER. ITS MAGNITUDE IS INDEPENDENT OF THE LOAD CURRENT AND IS INFLUENCED ONLY BY THE OUTPUT SETTING OF THE INVERTER. IT CAN BE VARIED STEPLESSLY AND THUS PERMITS CONTINUOUS VARIATION OF THE SPEED.

THE ACTIVE POWER TAKEN BY AN A.C. MOTOR FROM THE SYSTEM IS PROPORTIONAL TO THE TORQUE DELIVERED AT THE MOTOR SHAFT AND TO THE SYNCHRONOUS SPEED GIVEN BY THE NUMBER OF POLE PAIRS AND THE SYSTEM FREQUENCY (FIG.3). THIS POWER PM IS TRANSMITTED TO THE ROTOR VIA THE AIR GAP AND IS SUBDIVIDED AS FOLLOWS: THE COMPONENT PROPORTIONAL TO THE SPEED IS DELIVERED AT THE SHAFT AS MECHANICAL POWER PMECH' AND THE COMPONENT PROPORTIONAL TO THE SLIP IS COLLECTED AS ELECTRICAL POWER. PE1 (SLIP POWER) FROM THE SLIPRINGS. IN A SPEED CONTROL SYSTEM EMPLOYING ROTOR RESISTORS, THE SLIP POWER IS CONVERTED TO HEAT IN THE RESISTORS AND IS THUS LOST. IN THE SUBSYNCHRONOUS STATIC CONVERTER CASCADE, THE POWER COLLECTED FROM THE SLIPRINGS IS RECTIFIED BY RECTIFIER N1 AND FED BACK TO THE A.C.SYSTEM THROUGH INVERTER N2. THUS THE TOTAL POWER TAKEN FROM THE A.C. SYSTEM CONSISTS ONLY OF THE POWER TO BE DELIVERED AT THE SHAFT OF THE MOTOR PLUS THE SMALL MACHINE LOSSES AND THE ALMOST NEGLIGIBLE LOSSES OCCURING DURING FEEDBACK. ACCORDINGLY, THE SUBSYNCHRONOUS STATIC CONVERTER CASCADE HAS A VERY HIGH EFFICIENCY.

AS REGARDS MODE OF OPERATION AND OPERATING PERFORMANCE, THE SUBSYNCHRONOUS STATIC CONVERTER CASCADE IS VERY SIMILAR TO A SPECIAL DESIGN OF STATIC CONVERTER FED D.C. DRIVE WITH BUCK AND BOOST CIRCUIT (FIG.4).

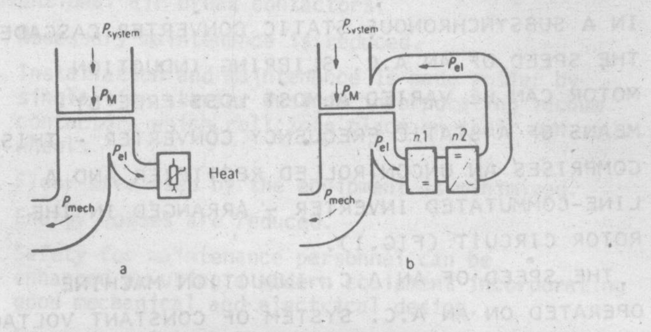


Fig.3. Power flow of an a.c. induction motor; a) with resistance control, b) within cascade

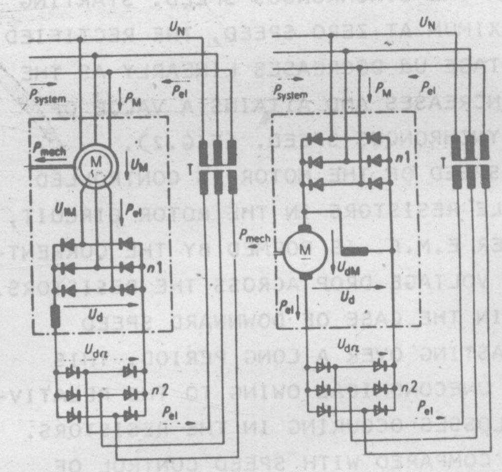


Fig.4. Comparison of the converter cascade with buck and boost control of a d.c. shunt motor.

IN THE D.C. DRIVE, THE MOTOR M AND THE UNCONTROLLED RECTIFIER N1 ARE ARRANGED IN OPPOSITE SEQUENCE AS VIEWED IN THE ENERGY FLOW DIRECTION. BOTH DRIVE TYPES HAVE THE FOLLOWING IDENTICAL CHARACTERISTICS: THE EXCITATION CURRENT IS DEPENDENT ON THE SYSTEM VOLTAGE AND CAN BE CONSIDERED CONSTANT IF SYSTEM VOLTAGE FLUCTUATIONS ARE NEGLECTED. ASSUMING THAT THE INDUCTION MOTOR HAS A TRANSMISSION RATIO OF 1:1 BETWEEN THE SYSTEM VOLTAGE AND THE ROTOR VOLTAGE (UN-UIM=UM) IS PROPORTIONAL TO THE SPEED. REFERRED TO THE D.C. SIDE, THIS VALUE CORRESPONDS TO THE ARMATURE VOLTAGE UDM OF THE D.C. MACHINE (FIG.5). THE INTERNAL VOLTAGE DROP OF THE TWO MACHINE TYPES IS MERELY DEPENDENT ON THE LOAD CURRENT AND THE INTERNAL RESISTANCE (IA . RA). THE TORQUE DELIVERED AT THE MOTOR SHAFT IS PROPORTIONAL TO THE ROTOR CURRENT OR ARMATURE CURRENT AT CONSTANT EXCITATION.

THUS THE BASIC CONDITIONS FOR THE SPEED/TORQUE BEHAVIOUR OF THE TWO DRIVE TYPES ARE IDENTICAL. BOTH HAVE A SHUNT CHARACTERICTIC, I.E. ASSUMING CONSTANT CONTROL SETTING OF THE INVERTER (=CONSTANT COUNTER E.M.F.) A LARGE CHANGE IN SPEED WHICH IS CAUSED BY THE INTERNAL VOLTAGE DROP OF THE MACHINE. IN THE CASE OF DRIVES WITH CLOSED-LOOP SPEED CONTROL, THIS DEVIATION IS COMPENSATED FOR BY CORRECTING THE COUNTER E.M.F.

REVERSAL OF THE TORQUE DIRECTION, I.E. BRAKING, IS NOT POSSIBLE WITH EITHER TYPE, SINCE AN INDUCTION MOTOR CANNOT PRODUCE BRAKING TORQUE IN THE RANGE FROM ZERO SPEED TO SYNCHRONOUS SPEED AND A D.C. MOTOR CANNOT PRODUCE BRAKING TORQUE UNLESS THE ARMATURE CURRENT OR FIELD CURRENT IS REVERSED.

A COMPARISON OF THE TWO DRIVE TYPES CAN, HOWEVER, ONLY BE MADE FOR THE SPEED RANGE IN WHICH THE INVERTER PRODUCES A COUNTER E.M.F. IF THE ARMATURE VOLTAGE OF THE D.C. DRIVE IS INCREASED BEYOND THE VALUE PRODUCED BY RECTIFIER N1 BY CONTROLLING CONVERTER N2 INTO RECTIFIER OPERATION, THE SPEED INCREASES FURTHER.

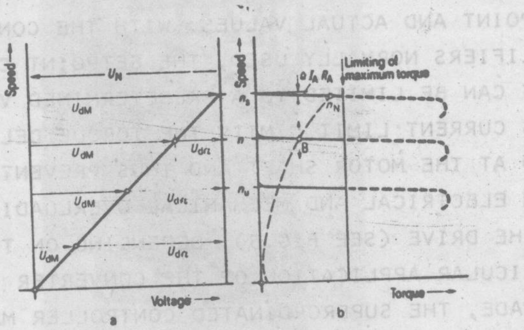


Fig.5 a) Speed as a function of the motor voltage UdM and counter e.m.f. Uda.
b) speed/torque characteristic with load characteristic of a fan. B is the adjustable operating point.

IN THE CASE OF THE SUBSYNCHRONOUS STATIC CONVERTER CASCADE, HOWEVER, THIS MEASURE DOES NOT BRING ABOUT ANY APPRECIABLE INCREASE IN THE SPEED SINCE IT IS ONLY POSSIBLE TO COMPENSATE FOR THE SMALL VOLTAGE DROP ACROSS THE CONVERTER VALVES AND THE SMOOTHING REACTOR. THE SPEED ATTAINED IS MERELY THE MAXIMUM VALUE THAT WOULD BE REACHED IF THE ROTOR WINDING WERE SHORT-CIRCUITED DIRECTLY ACROSS THE INPUT OF THE RECTIFIER.

2 CLOSED-LOOP CONTROL

SINCE THE OPERATING BEHAVIOUR OF THE TWO DRIVE TYPES IS IDENTICAL, IT IS ALSO POSSIBLE TO EMPLOY THE SAME CONTROL CONCEPT. THE TYPE OF CONTROL NORMALLY EMPLOYED FOR THE SUBSYNCHRONOUS STATIC CONVERTER CASCADE IS THEREFORE A CLOSED-LOOP SPEED CONTROL WITH SECONDARY CURRENT CONTROL. ANY DEVIATION OF AN ACTUAL SPEED VALUE SENSED BY A TACHOGENERATOR G FROM A SPEED SETPOINT VALUE OBTAINED FROM A POTENTIOMETER OR SUPERIMPOSED CONTROLLER IS AMPLIFIED BY THE SPEED CONTROLLER AND FED TO THE SECONDARY CURRENT CONTROLLER IN THE FORM OF A CURRENT SETPOINT VALUE. A NEGATIVE SPEED DEVIATION THUS CAUSES AN INCREASE IN THE CURRENT SETPOINT VALUE WHICH IS ACCOMPANIED BY AN INCREASE IN