Variable Speed AC Drives: The Past and Current Status

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Abstract: *This paper presents a review of the state-of-the-art in Variable Speed Drive (VSD), through Power Electronics application and control. The major development trends even in the past had dominance of AC drives in a variety of applications, with the squirrel-cage and wound rotor induction motors as the preferred machine in most cases [1-4, 28]. Particularly striking has been the rapid ascendance of Power Electronics [5-12] and Pulse Width Modulation (PWM) technique in conjunction with Power Semiconductor Devices (PSDs) as the predominant switches [13-25,28] in industrial applications and control, ranging from fractional kilowatts to several megawatts. Recent developments in Pulse Width Modulation (PWM) technique and functional control of PWM drives [17,26,27,31-33,35-38,40-55,58-67,70-76,78,100], their user interface, menu driven interface and programmability have become very predominant [29,34,39,70,109,110]. The protection schemes contributing strongly towards knowledge based and intelligent drive control [77,85-89,92-99,101-102,105-109] have also been highlighted. The review paper thus covers several of these aspects, starting from the basic drive system and its control. It is hoped that this paper will benefit the researchers to have a quick birds' eye view of the past and current status in Variable Speed Drives.*

Keywords: *Variable Speed Drives; Pulse Width Modulation; Squirrel-Cage Induction Motor; Variable Frequency Operation; Inverters; Knowledge Based Protection; Power Semiconductor Devices; Intelligent Drives.*

I. INTRODUCTION

The squirrel-cage induction motors are the largest electrical energy consumption devices in the world because of their being a versatile and popular VSD [1-4]. The variable speed drive system mainly requires variable voltage and frequency supply, which is invariably obtained from a three-phase voltage source inverter (VSI) [5-20]. A number of Pulse Width Modulation (PWM) schemes have been next used to obtain variable voltage and frequency supply from an inverter [17,21,74,76,79,87,88]. The reliability of Power Electronics Devices (PSDs) Circuits and Systems, as compared to those of conventional Electrical Equipment and Power Systems has been a subject of great concern for the system designers and application engineers [6,7,9,12,15,16,30]. This concern has been mainly due to very low thermal and surge withstand capability, rate of change of voltage as well as rate of change of current of the PSDs, as compared to those of the electrical machines, transformers and other power system equipment [6,12,15,16,30,57,68,69]. As such, the system reliability of Power Electronics has been rather vulnerable. It therefore attracts importance from protection point of view in all Industrial, Commercial, Aerospace, Domestic and Military applications [77]. Thus, it has become essential for system designers to gather complete and true knowledge about the fault mode behavior and analyses of any converter/inverter system and Power Semiconductor Devices used therein [84,85-89,93,94,100,101]. From the point of view of Knowledge Based Protection, Reliability, Improved System Performance and Fault Tolerance Control, investigations have also been made in designing new systems [106,110].

The work reported in this review paper attempts to present the state-of-art, in variable speed AC drives, using the Voltage Source PWM inverters that are used for the control of drives, highlighting the application of Intelligent Knowledge based systems, for the fault diagnosis and its possible removal and/or isolation.

II. BRIEF STATUS OF VARIABLE SPEED DRIVES

Induction Motor has been established as the workhorse of industry ever since the 20th century [1-4,9-20]. Although, the recent developments in *Power Electronics* and Controls have brought forth some very significant drive alternatives like the *Switched Reluctance Motor* [90,91], *Permanent Magnet* and *Brushless DC Motor* [56,82,103,104], these have not yet become very popular and cost effective for a wide range of application, especially in the damp-proof, dust-proof and fl[illegible]proof environments. Therefore, the widespread [illegible] induction motor is still economically viable as well as popular and is likely to continue for the next few decades. The induction motor, especially the squirrel cage rotor type is mostly popular in the lower horse power ranges, while the slip ring type is common for higher horse power ranges as well as to meet certain specific torque requirements like that of Cranes and Hoists applications [28,37,53,55]. The squirrel cage motors are economical, robust, compact, and highly efficient [[illegible],23,60]. These motors are practically ma[illegible]e free and can be designed in the damp-proof, [illegible]-proof and also flame-proof enclosures. More than 90% of motors produced worldwide are of squirrel cage rotor type and this trend is likely to continue further. Tables 1 and 2 give a brief summary of a variety of AC and DC drives for variable speed operation and for pursuing principal Research & Development activities respectively.

Table 1: Types of Variable Speed Drives

DC Drives	About 50% of all drives (above 1 KW) are DC motor drives, for wide speed control range and their fast response time. These characteristics are possible due to the inherent orthogonal relationship between the armature and field.
AC Drives Range	Type of AC Drives.
Up to 5 KW	Voltage Controlled induction motor is preferred.
Up to 100 KW	Variable Voltage Variable frequency Inverter with either quasi-square or PWM output as per the performance requirement
Up to 500 KW	PWM inverter driven induction motor using GTOs, BJTs or IGBTs. All these are generally microcomputer controlled.
Up to 5 MW	PWM inverter driven induction motor, using thyristor. The GTOs/IGBTs are gradually replacing thyristors with Microprocessor based control.
All large drives beyond 2 MW	Usually either Inverter fed synchronous motors, or Cycloconverters based doubly fed induction motors, or slip-energy recovery systems. The Vector Control of induction motors is also preferred, where the system cost is not the major concern.

Table 2: Variable Speed Drives - Principal Areas of R & D.

Inverter Control Strategies	Harmonic elimination and reduction. Sophisticated variations of PWM inverters.Field orientation control or Vector control of air-gap field & stator mmf using real-time computation.
Variable Speed Drive Control	VSD is often installed (as energy saving).Scope for use as a sophisticated controller, to eliminate unnecessary mechanical components.
Improvements of PSDs	Present Devices that are popular are GTO, MOSFET, IGBT, BJT, MOT, SIT, SITHComposite Devices are under development e.g. MCT, SIT, SITH & MOT, which are promising. Continuous improvements in ratings of these devices are taking place.
Unconventional motor configurations	Switched reluctance motor Permanent magnet brushless DC motor Disk drives (spindle motor) and motors from high energy permanent magnet materials (Neodymium iron even better than samarium cobalt).

A suitably designed PWM Inverter System, using Power Semiconductor Devices (PSDs) feeding a squirrel-cage rotor motor, forms the most ideal Variable Speed Drive (VSD) for a variety of industrial applications [31-36,38-43,46-52,54-55,58-66,72,76-79,81]. The work reported in this review paper therefore concentrates on squirrel-cage rotor induction motor fed by PWM Inverters as the base for the control analysis and hence the development of complete control circuits for inverter applications.

The paper therefore begins with the very basic aspect of describing the principle of induction motor operation, its torque-speed characteristics and some significant performance analyses and limitations; with specific reference to obtaining the Variable Speed Operation mainly through the Voltage Source PWM Inverters and also some significant research developments.

III. OPERATING PRINCIPLE AND EQUIVALENT CIRCUIT

Normally, the voltage applied to the stator terminals of the induction motor is three-phase balanced supply. It therefore results in generation of a uniform magnetic field, rotating at synchronous speed. The rotor currents also produce a rotating field at synchronous speed.

These two fields together produce the air gap flux. At normal supply frequency and voltage, this flux has a constant value. The parameters air gap flux f, the supply voltage V, and the frequency f, are related as under:

$$\phi \propto V/f \qquad (1)$$

It may be mentioned that the design of induction motor is well optimized. It operates with the core near to saturation i.e., any increase of input voltage is likely to take it into saturation, thereby increasing the magnetizing current disproportionately and adversely affecting the efficiency. Such increase of voltage is generally avoided. Maintaining the flux level in the air gap at its rated value (V/f = constant) is an essential requirement of conventional speed control, as well as variable frequency operation through Power Electronic converters and inverters, especially the PWM inverters [9,15,16,17,21,57,68,69].

Whenever, the induction motor is loaded, its torque and power requirements increase. As such, the stator current also increases. The limit of safe allowable temperature rise of the induction motor constrains the stator current and hence the motor output. It may be said that while the applied voltage and frequency are tied up by saturation considerations; the output power and torque are constrained by motor thermal consideration.

The equivalent circuit of induction motor is shown in figure 1, with its conventional parameters assumed as constant over the entire operating range. Voltage across the magnetizing circuit impedance X_m and r_m in parallel determines the air gap flux of the motor. Although, the voltage drop in stator winding i.e., across X_1 and r_1 is considered negligible under normal operation, this approximation does not hold good for low operating speeds and hence at low operating frequencies. A definite slip is essential for the operation of induction motor. However, it increases as the torque requirements increase. The power input to rotor resistance r_2/s as shown in figure 1, represents the power transferred to the rotor and hence the developed torque [15,68,69].

From the equivalent circu t as shown in Figure 1, the following fundamental points are worth noting and are also worth remembering:

- The shunt branch r_m represents the iron loss component. If the applied voltage is reduced, the iron losses will also reduce.
- Voltage across the shunt branch X_m determines the air gap flux. If the applied voltage is reduced, the magnetizing current would also reduce.
- Whenever, the motor is loaded, the voltage drop across primary impedance (r_1 and X_1) reduces the net voltage available for air gap flux. However, at nominal frequency and normal loads, this drop is small (about 5%) and is therefore generally neglected.
- Although, the values of r_2 and X_2 parameters are represented as constant in the equivalent circuit as depicted in Figure 1; these values always vary with the slip. At low values of slip, r_2 can increase substantially (twice or even more). This keeps the motor starting current within limits, without adversely affecting its normal running performance.

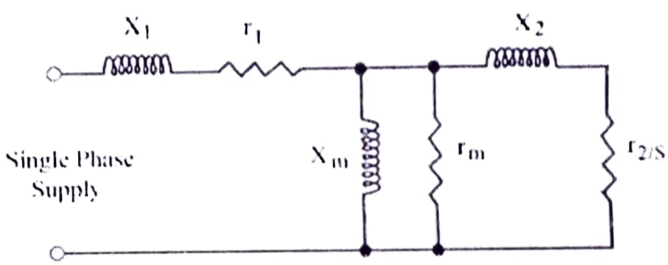


Fig. 1: Per Phase Equivalent Circuit of Induction Motor

While writing this review paper and considering the application of PWM Inverters for the control of squirrel-cage rotor motors, the above points are kept in mind.

Table 3 displays the values of the equivalent circuit parameters of some typical three-phase, 440V, squirrel-cage rotor induction motors referred to the stator side.

Table 3: Equivalent Circuit Parameters of Four Pole Induction Motor

Horse Power	'r_1' (Ohms)	'L_1' (mH)	'r_2' (Ohms)	'L_2' (mH)	'r_m' (Ohms)	'X_m' (Ohms)
0.75	15.08	50.0	10.08	50.0	2365	355.0
1.00	10.50	41.0	8.01	35.0	1808	235.0
1.50	7.40	22.2	5.21	21.7	1669	152.7
2.00	5.66	18.5	4.10	18.3	1424	14307
3.00	3.40	10.1	2.34	9.6	903	903
4.00	2.84	7.7	1.98	7.5	634	634
5.00	1.43	6.3	1.39	5.9	705	705
7.50	1.22	4.7	0.94	4.9	616	616
10.00	0.83	3.2	0.59	3.24	466.6	466.6

A. *Steady State Performance Characteristics*

The steady-state performance characteristics of induction motor are shown in figures 2 and 3. In general, the motor performance in terms of its efficiency, power factor and speed drop from the no-load to full-load, improves as the horsepower rating of the motor moves upwards. However, it is also worth noting that the steady-state performance deteriorates marginally as the number of poles increases beyond four. From the Power Electronics Converter control and design point of view; some very significant information on the steady-state performance characteristics is relevant and is briefly discussed in the following sub-sections.

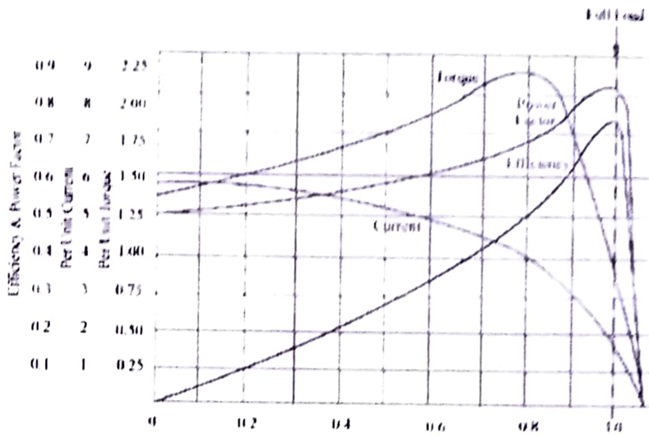


Fig. 2: Steady-State Performance Curves of Typical Three-Phase Induction Motor

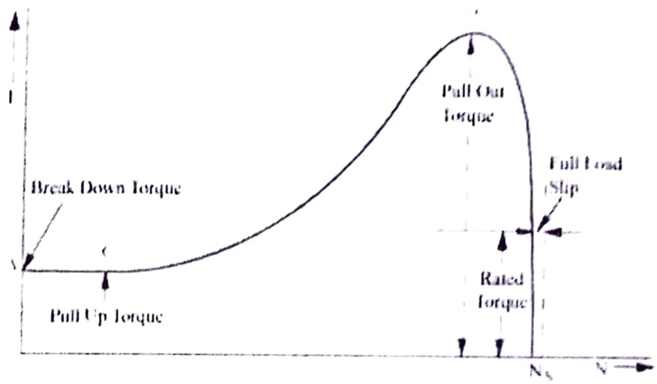


Fig. 3: Typical Torque Speed Characteristic Curve

1) *AC Mains Supply Current:* For a well-designed motor the no-load current is of the order of 15-20% of its full load rated value. The supply current increase as load on the motor goes up. It may be mentioned that current at the instant of starting is generally 6-8 times the rated current. It drops only when the motor speed reaches close to the rated speed.

2) *Power Factor:* The power factor is generally very poor almost equal to 0.5 under low loads, because of relatively high component of magnetizing current. However, the power factor improves as the load on the motor increases.

3) *Efficiency:* Efficiency increases rapidly from a very low value as the load on the motor increases from no-load to the full-load. At full-load, the efficiency is in the range of 80-90%. Efficiency at low speeds is further low and is of significant academic interest, especially in the context of losses and heating, when operated from the PWM Voltage Source Inverter supply.

4) *Speed Drop:* Since induction motor is almost a constant speed drive, the speed drop from no-load to full-load is always a good index of its performance. This drop is in the range of about 3-6% with medium horsepower motors. Unlike that of DC shunt motor, the speed drop in induction motor is fairy linear with load torque in the stable region of its operation, as depicted in Figure 2.

5) *Torque:* The torque-speed characteristic of induction motor is always a representative of its performance. Figure 3 depicts a typical torque-speed curve. The maximum torque i.e., the pull-out torque is represented by the point 'P' on the curve as shown in Figure 3. This torque is about three times higher than the rated full load value. It may be remembered that the ratio of pull-out to full load torque is a measure of the stability of motor operation. Further, the higher value of this ratio also avoids crawling of induction motor at the instant of starting against load.

The value of pull-out torque can be increased by reducing X_2 and to some extent by reducing r_1 or X_1. This can be done during design of the motor. Further, these parameters are of great concern, when the PWM Inverter and its protection systems are designed and fault mode analysis with knowledge based protection system is done.

Point 'A' on the torque-speed curve as shown in Figure 3 represents the starting torque; this torque too should be adequately large to ensure a healthy motor start. Increase in the rotor resistance r_2 increases the starting torque. However, it also increases rotor losses, and hence reduces the efficiency as well as increases the full load speed drop considerably. Therefore, a well thought compromise between these parameters needs to be done while designing the motor for being fed through converter/inverter.

B. *Operating Characteristic Requirements*

The factors like simplicity, robustness, low cost and no maintenance property of squirrel-cage rotor motors have made these motors the 'workhorse of industry' – so much so that wherever possible, the user tries to adopt the squirrel-cage rotor motor, rather than seeking other alternatives. This tendency has spawned a variety in squirrel-cage rotor motors' design and construction. According to NEMA classification, these motors are placed in four distinct categories – named as class A, B, C & D respectively.

1) *The Class A motor:* Among the identified types of classes mentioned as above the Class A motor is most commonly used in industry. This motor possesses a single cage rotor with the following features:

- Low rotor resistance
- Low full load slip
- High efficiency
- The Class A motor has the highest starting current and can also provide the lowest starting torque as compared to all other classes.
- Suitable to drive all loads, which have stable speed requirements.
- The stable operating range of the motor is limited to a narrow speed variation close to the synchronous speed.

2) *The Class B motor:* This motor is less costly than Class C, therefore it is a low cost alternative to Class C and has the following features:

- This motor is costlier than the Class A and Class D types.
- It uses a deep bar rotor cage and provides almost the same benefits as that of the Class C motor.
- For new installations Class A motor with a drive has been a good competitor to Class B, due to its higher cost.
- The cost is although higher only by about 10% to 20%, it still has a higher disadvantage.

It may be mentioned that the Class A motor with a suitable converter may also be considered as an alternative to the Class C. However, the converter/inverter and motor combination have to be chosen to supply the high accelerating torque, to the extent of about 200-300% higher. The user may have to therefore settle for higher converter design and a slightly higher motor rating than with that of the Class C as an alternative.

In the Class B motor the operation on low frequency results in prolonged high currents in the inner-cage. The cage motor and the converter/inverter circuit may also be therefore adequately designed to withstand the resulting heating and/or higher ratings of the PSDs. Such additional heating has to be well thought and weighed against the increased accelerating torque available due to both cages as well as converter/inverter circuits carrying substantial currents.

3) *The Class C motor:* This motor is designed to meet the following features:

- It has a double cage rotor motor.
- The high resistance of the outer cage provides the necessary starting characteristics.
- The low resistance of the inner cage meets running requirements.
- It is worth noting that the full load slip is somewhat higher.
- The efficiency is lower, when compared to that of the Class A motor.

4) *The Class D motor:* This motor too is of single cage type. The Class D motor is a poor, but an economical substitute for squirrel-cage rotor motor when compared with the Class A motor. It has the following features:

- High rotor resistance.
- The starting current is low.
- Full load efficiency is poor.
- It provides a high starting torque, equal to the pull-out torque.
- Delivers stable operation throughout the speed range.
- This motor is preferred when stable operation is required for all speeds even for flat torque type loads.
- Roller table drive is a typical application suitable to this class.

The applications like induced draft fans, blowers, etc., require the motor to maintain a fixed speed. Nevertheless, their high inertia demands a very high starting torque. Therefore, the low starting torque of Class A motor is not enough to accelerate against loads. Thus, the Class D motor is suitable to meet these requirements but, its full load efficiency is poor.

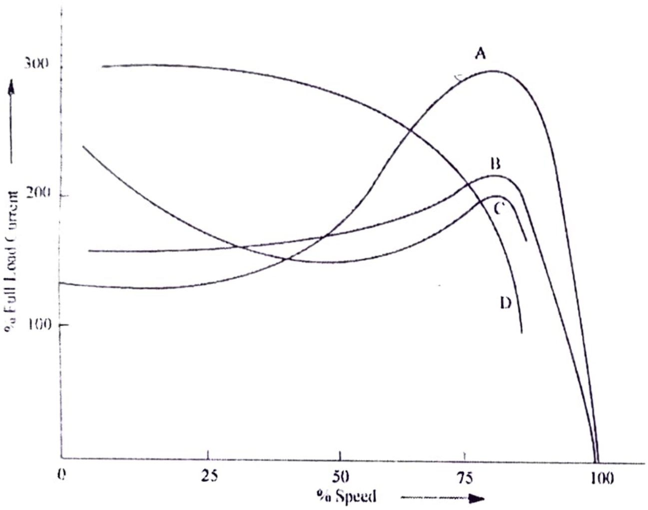


Fig. 4: Torque Speed characteristic of four classes of Squirrel Cage motors.

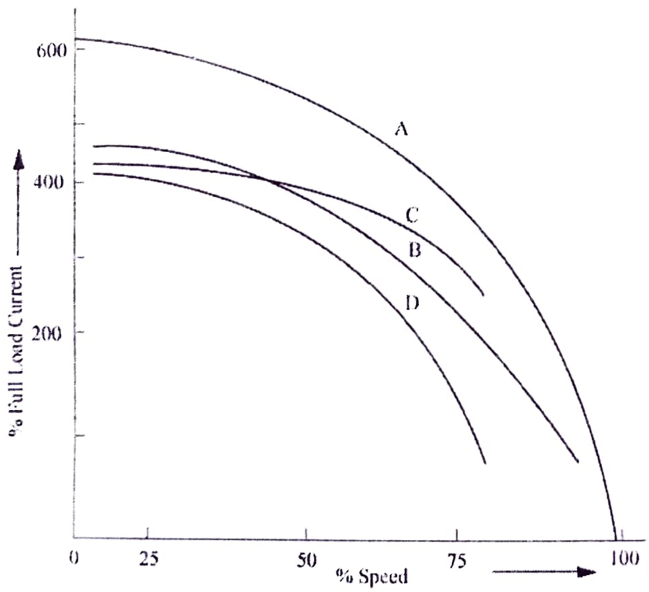


Fig. 5: Current Speed characteristic of four classes of Squirrel Cage Rotor motor

C. *Low Frequency Operation*

Low frequency operation of induction motor is a very common phenomenon within the scope of Variable Speed Drives operation and converter/inverter feeding the motor. As and when the input frequency and voltage are reduced (maintaining the ratio V/f constant), the motor speed reduces proportionately. Therefore, cooling of motor i.e., ventilation and the heat that can be carried away get reduced. As such, the motor cannot sustain the same level of load due to practical limitations. These limitations are broadly of two types:

- Thermal Considerations
- Stator Voltage drop

The thermal limitation comes due to lack of ventilation and cooling due to the low speed operation. The current derating required is normally as shown in figure 6. This limit is representative of the two and four pole motors. However, for motors of larger number of poles and also the motors with separate ventilating fans, the level of 50% derating at zero speed can be revised upwards to about 60%.

The voltage available across the shunt branch for the production of air gap flux as shown in figure 1 is always less than the supply voltage by an amount equal to the stator voltage drop.

$$E = V - IZ \qquad (2)$$

Where, E, V, I and Z are the stator emf, applied voltage, current and stator winding impedance respectively. All of these are phasor quantities.

At 50 Hz, the voltage drop IZ constitutes about 5 to 10% of rated voltage. Therefore, in the equivalent circuit analysis it is always assumed that the magnitudes of E and V are more or less equal. However, as the supply frequency is reduced to low values, the stator voltage drop becomes dominant; especially at high load levels. Since the stator reactance is low at low frequencies, the stator drop in this case is essentially

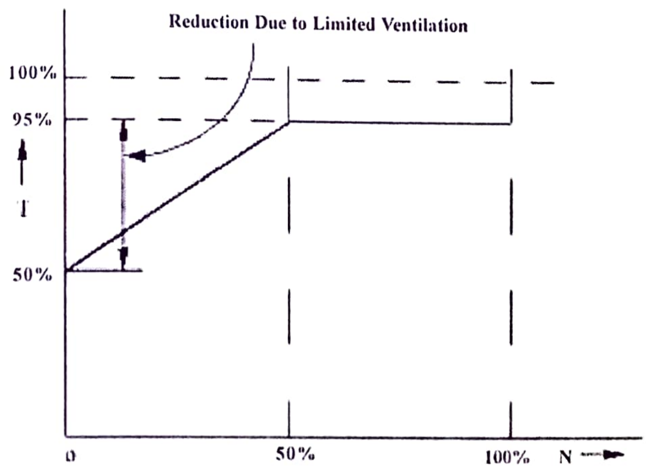


Fig. 6: Thermal Consideration of Induction Motor for Low Speed

the drop in stator resistance. In order to maintain the rated air gap flux level and also to get the rated full torque output from the motor, the applied voltage has to be compensated. As such, the applied voltage needs to be boosted by an amount equal to the stator voltage drop. This is very popularly referred to as '*IR compensation*'.

The actual compensation required is dependent on the factors like input supply frequency, motor parameters – (r_1 and X_1), actual load, thermal history of load and harmonics. It may be mentioned that fluctuating loads add to utter confusion and the IR compensation is somewhat a complicated issue, more easily talked about than actually implemented. Some low cost converters/inverters do have a 'fixed' voltage boost at low frequencies. However, a well designed converter/inverter system may provide adequate flexibility to adjust the level of IR compensation to suit to the motor and the load [45,50,109].

IV. VARIABLE FREQUENCY OPERATION OF INDUCTION MOTOR

The advent of PSDs as described in this review paper, leading to the design and development of inverters systems has added a new dimension to induction motor control by making its operation with variable frequency supply possible. Equation (1) vividly demonstrates that if the supply frequency is reduced, the voltage too is to be proportionately reduced, to maintain the air gap flux level at its rated value. It may be of interest to remember that increase of flux above rated value is not practical due to saturation. Figure 7 depicts the torque speed characteristics of induction motor for a set of three selected frequencies.

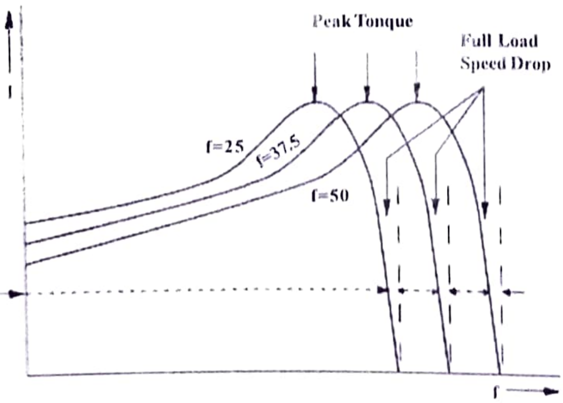
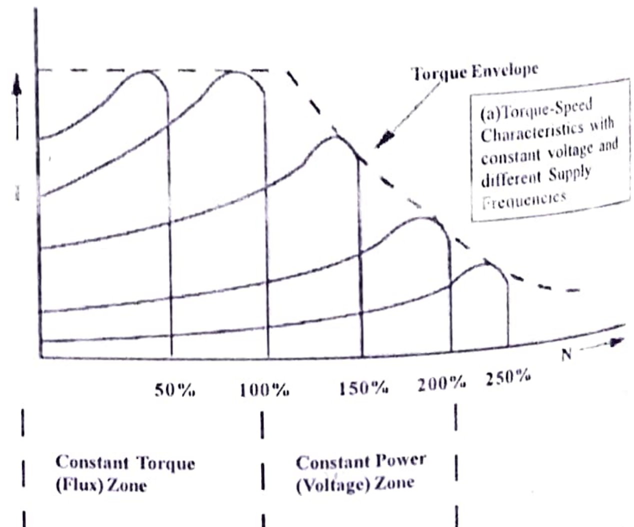


Fig. 7: Torque-Speed Characteristics of Induction Motor with Different Supply Frequencies

The following observations are made from the torque-speed characteristics as depicted in figure 7 on variable frequency operation of induction motor and hence the application of PWM Voltage Source Inverters:

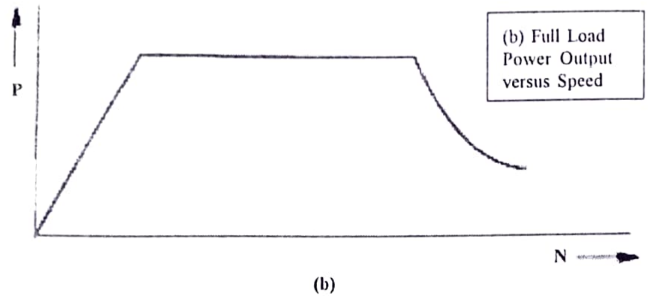
- As the supply frequency f is reduced, the maximum speed attained by motor reduces proportionately.
- The speed drop from no load to full-load remains generally constant for all supply frequencies as depicted in the figure.
- The magnitude of pull-out torque remains the same at all set values of f.
- Torque developed at the full-load current remains the same for all set values of f.
- The power output decreases as frequency is decreased.
- This operation is popularly called the 'constant torque operation'.

For operation above 50 Hz, theoretically the increase in the input voltage should be done; beyond its rated value in proportion to frequency. This needs to be done in order to maintain constant air gap flux as per equation 1. However, practically this is not recommended from the point of view of insulation safety at higher voltages. Instead, alternatively the supply voltage is kept constant at the rated value and frequency is increased. In case the flux decreases, due to increase in f the full-load torque will decrease [57,68,69]. However, the output power remains constant, because this region of operation is of constant voltage or constant power as shown in Figure 8 (a).



(a)

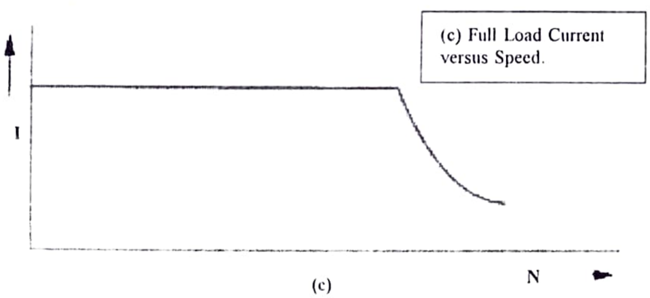
(a) Torque-Speed Characteristics with constant voltage and different Supply Frequencies

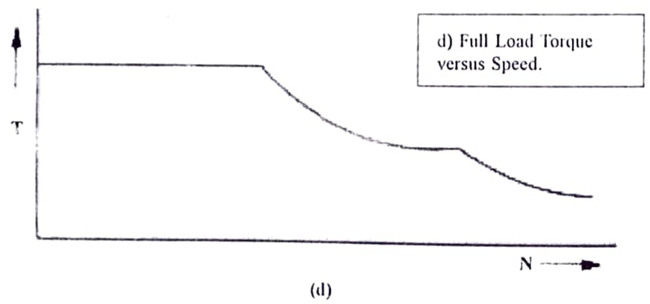


(b) Full Load Power Output versus Speed

Fig. 8 (a)-(b): Operation of Induction Motor with constant Voltage & different Supply Frequencies

It may further be noted, that the pull-out torque also reduces steadily. The constant voltage zone normally extends up to 180-200% of the base speed. Beyond this value, the reduction in pull-out torque and the requirement of stable operation restrains the full-load current of the motor to lower values. The admissible full-load current is taken as inversely proportional to frequency of supply. While the torque-speed characteristics and their envelopes are shown in Figure 8 (a), the full-load power, current and torque values are shown and plotted in the figures 8 (b) to (d) respectively. Typically, such wide range of speed control is required in applications like, electric traction and battery operated vehicles etc.





(c) Full Load Current versus Speed. (d) Full Load Torque versus Speed.

Fig. 8 (c)-(d): Operation of Induction Motor with different Supply Frequencies

When the induction motor is operated above synchronous speed, the motor develops a torque in the negative direction. In this case the negative torque implies that motor is taking the mechanical energy from the load and is acting as generator, so as to feed energy to the mains in the electrical form. The torque increases steeply with slip in the negative direction. In this manner full 100% regenerative torque is generated with negative full load current at a slip almost equal in magnitude to the full load slip. The energy in the load is transferred to the motor and dissipated in its rotor in the form of heat. It may be worthwhile to mention here that generally the rotor can withstand higher temperatures as compared to that of the stator.

A. *Four Quadrant Drive Operation*

Depending on the requirements, the induction motor may be required to drive different types of loads e.g., lifts, hoists, cranes, pumps, traction vehicle etc. Four different situations arise in variable speed drives operation as illustrated in the four such cases of figure 9. In these figures the motor shaft is shown driving a hoist type load.

1) *Quadrant 1:* During this quadrant of operation the load W_1 is assumed to be heavier than W_2. It is being hauled up by the motor, with shaft rotating in counter-clockwise direction as shown in figure 9. The motor is delivering power to the load. In this case the torque developed by the motor and the motor rotation are both in the same direction.

2) *Quadrant 2:* As seen in figure 9, the load W_1 is assumed heavier them W_2 and is therefore being lowered. The motor now rotates in clockwise direction. Torque developed by motor is in counter-clockwise direction. In this case motor receives power from the load. The same may be resistively dissipated or fed back to the mains.

3) *Quadrant 3:* In this case the load W_2 is assumed to be heavier than W_1 and is being hauled-up by motor rotating in clockwise direction. Both torque and speed directions are reversed as compared to operation in the first quadrant as shown in Figure 9. However, in this case too motor delivers power to the load.

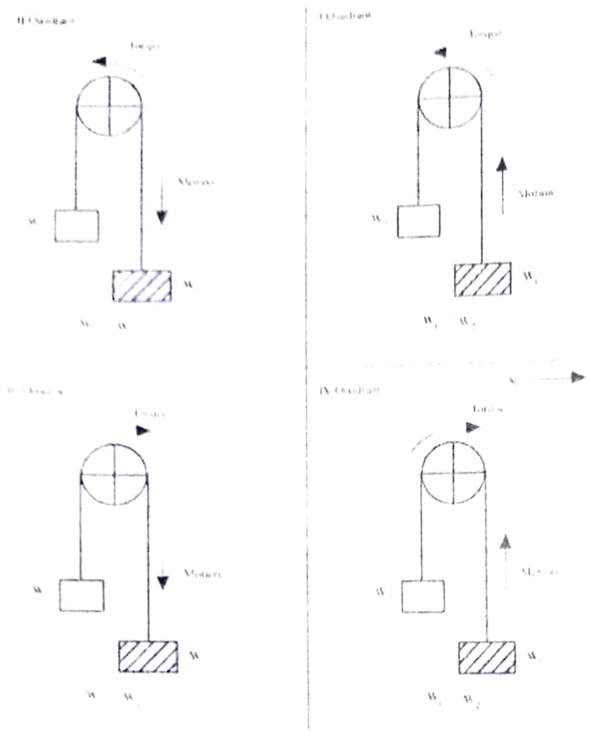


Fig. 9: Four-Quadrant Operation of Induction Motor

4) *Quadrant 4:* Let us assume that the load W_2 is heavier than W_1, and W_2 is being lowered. Motor rotates in counter-clockwise direction, but develops torque in the clockwise direction. In this case too as has been with Quadrant 2 operation, the motor receives power from the load. The same may be resistively dissipated or fed back to the mains.

From the above noted explanation it is clear that the versatile drives are capable of operation in all the four quadrants. The operation in first or third quadrant means power transfer takes place from electrical mains to the load through the motor. This forms the primary operating mode for the motor. On the other hand the operation in the second or fourth quadrant requires extraction of power from the load by the motor. The regenerative energy may thus be dispensed in a number of ways.

B. Braking

While the four-quadrant drive operation has been discussed in the preceding sub-section, the braking of induction motor is discussed in this section. With some very simple arrangement, the induction motor can be made to work for braking e.g., the eddy current brake, plugging etc. A more elaborate scheme provides for dissipating the energy in an external resistor. Although, the induction motor per se is not amenable to this kind of operation; when operated through a variable voltage variable frequency inverter; the braking process becomes attractive and effective proposition [92]. The reversal of phase-sequence of input supply popularly known as 'Plugging' enables braking operation down to zero speed, but the de-energization of motor has to be done in time.

Eddy current braking, resistance braking and plugging are the methods wherein energy is dissipated as heat and is wasted. However, the regeneration mode of operation allows extracting energy from the load and feeding it to the mains after necessary conversion to 50 Hz. In this case the energy in the load is not wasted; but is retrieved and returned to supply. The major limitation is that regeneration is effective only above some reasonable levels of motor speed.

So far the induction motor operation in the first quadrant had been more popular in conventional control. Some specific applications that demand operation in the second or fourth quadrants have until recently been done through the DC motors. However, with the advent of Power Semiconductor Devices and subsequent design of inverters especially with the PWM technique has made the wound rotor induction motor as a good contender for the DC drive [28,68,69], as depicted in figure 10. On the other hand the squirrel cage induction motor when combined with the inverter makes a very good drive combination explained as under:

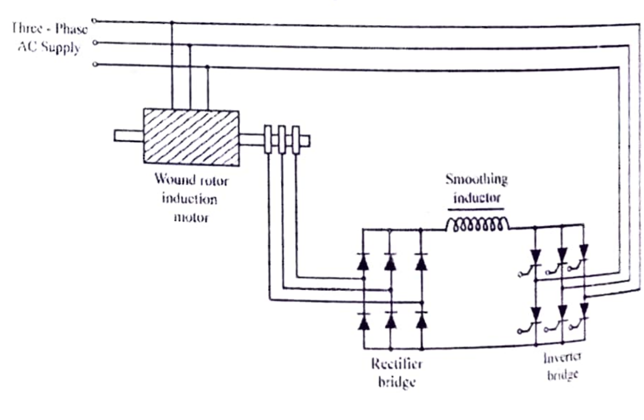


Fig. 10: Induction Motor & Sub-Synchronous Static Converter

Most of the loads (number wise) require to be driven at a constant speed by a squirrel-cage rotor motor at a fixed frequency. Amongst those, which call for variable speed application, a substantial percentage requires a variable speed drive in the forward direction only, fans and pumps are typical examples of this application. Such drives are 'single quadrant' drives and the squirrel-cage rotor motor with adjustable frequency supply has so far been well suited for 'single quadrant' drive application.

Some applications require braking of a simple type. Typically, some machine tool applications require a job to be driven to a particular location; but not beyond. However, in case it continues; necessary braking is required to be done. In this kind of application the drive motor is required to be operated in two-quadrant mode, generally the first and the second. Typical squirrel-cage rotor motors provide braking torque when excited for reverse direction of rotation i.e., the phase-sequence is changed for the reverse direction of rotation. If excited at 50 Hz, the portion PS of the torque-speed characteristic curve as shown in Figure 11 represents such braking.However, in case it continues; necessary braking is required to be done. In this kind of application the drive motor is required to be operated in two-quadrant mode, generally the first and the second. Typical squirrel-cage rotor motors provide braking torque when excited for reverse direction of rotation i.e., the phase-sequence is changed for the reverse direction of rotation. If excited at 50 Hz, the portion PS of the torque-speed characteristic curve as shown in Figure 11 represents such braking.

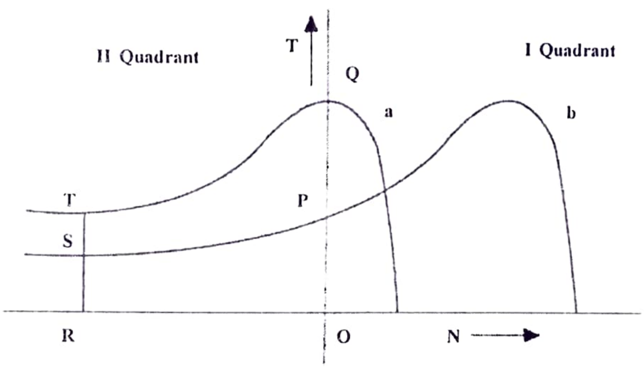


Fig. 11: Torque-Speed Characteristics in Two Quadrants

The break torque RS as shown in Figure 11, at any speed is less than the starting torque OP. Further, during the process of braking the energy of the load is dissipated in the motor. Decrease in the input supply frequency yields a larger level of braking at the same operating current. This is depicted by curve 'a' as shown in figure 11. The torque 'TR' with low frequency excitation is larger than 'RS' with 50 Hz supply. Lowest possible frequency of supply is therefore desirable. Improvement in braking torque is achieved due to an improvement in the power factor. Some significant points to remember during braking are mentioned as under:

- Braking torque is lower than the starting torque.
- Power factor during braking is inherently low, lower than that at starting.
- Energy of the load is transferred to the motor and dissipated in its rotor. It may be worthwhile to mention here that the rotor can withstand higher temperatures as compared to that of the stator.

When operated above the synchronous speed, the induction motor develops a torque in the negative direction as shown in figure 11. In this case the negative torque implies that motor is taking mechanical energy from the load and is acting as a generator to feed it to the mains in the electrical form. The torque increases steeply with slip in the negative direction. Full 100% regenerative torque in this manner is generated with negative full-load current at a slip almost equal in magnitude to the full load slip.

When operated at 50 Hz from the AC mains, it is not practically possible to operate motor in this manner and extract energy from the load. However, when the motor is fed from a variable frequency inverter, and is to be decelerated, the supply frequency can be adjusted such that the induction motor performs with a negative slip and operation is in the region PR of the torque-speed characteristic as shown in Figure 12. In fact, suitable control circuit can be designed to continually adjust the frequency to make full current pass through the motor and have full load torque produced.

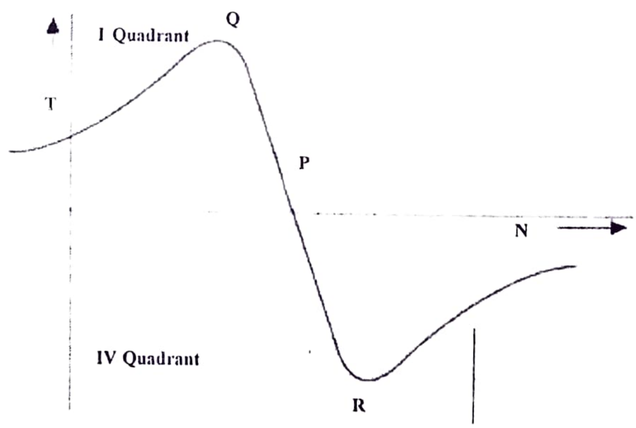


Fig. 12: Complete Torque-Speed Characteristic of Induction Motor

V. INDUCTION MOTOR VARIABLE SPEED DRIVE (VSD) SCHEMES

Having discussed the four quadrant, braking and regenerating operations of induction motor, it is now relevant to explore its variable speed operation achievable through inverters/converters. The inverter circuit scheme generally used with Variable Speed Drives (VSD) can be arranged in the most general form as shown in Figure 13. The three-phase supply from the AC mains

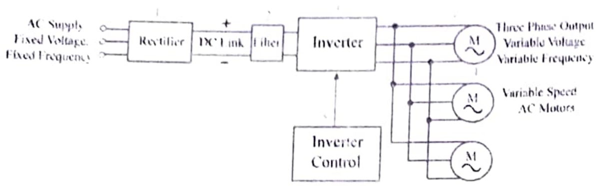


Fig. 13: Block Diagram of a Basic Variable Frequency Variable Voltage Output Circuit

is converted to DC through a set of Power Semiconductor Devices (PSDs) represented by rectifier block marked '1' in figure 13. These PSDs could be any either controlled or uncontrolled; either voltage gated or current gated. The choice of PSDs e.g., diodes, SCRs, BJTs, IGBTs, MOSFETs or GTOs depends upon the specific requirement and rating of the inverter in demand. A reference to this effect may be made to Tables-1 and 2.

Since the output of block '1' contains harmonics ridden voltage over the desired average DC value, there is a standard practice to filter this voltage by the filter block '2' as shown in figure 13. The output of '2', which is a filtered DC is made to switch Power Semiconductor Devices sequentially by inverter block '3', so as to deliver a three-phase AC output. This block too, is suitably designed with a set of PSDs to accomplish the necessary switching either to obtain a square or a quasi-square or a PWM output; as the case may be. In order to be able to run the VSD, an induction motor in this case, the converter/inverter circuit must have the capability to meet the following minimum requirements.

- Adjustment of output frequency.
- Adjustment of output voltage.
- A relationship of V/f ratio maintained constant as per drive requirement

These controls are suitably designed and developed to become consistent with the requirements of *square, quasi-square* or *near sinusoidal* and *sinusoidal* output. However, as mentioned above, the choice of output to be either *square, quasi-square* or *near sinusoidal* depends upon the horse power rating as well as drive performance requirement as demanded by a particular application [5,9,10,11,12].

A. Pulse Width Modulation Technique

Unlike the conventional methods of inverter voltage and frequency control, this method deals with obtaining a near sine wave across the load terminals. Further, it is possible to control the voltage and frequency in just a single inverter stage. A technique to achieve this is called Pulse Width Modulation (PWM). As depicted through the train of pulses of figures 14, the load voltage waveform is a width modulated periodic wave. Thus, the output voltage control is obtained by controlling the width and also the number of pulses during each half cycle. The control technique named as Pulse Width Modulation is suitable for motoring as well as regenerating modes and also for selective harmonic elimination. Figure 14 depicts sine modulation because the pulse width in each half cycle is modulated following a sine pattern.

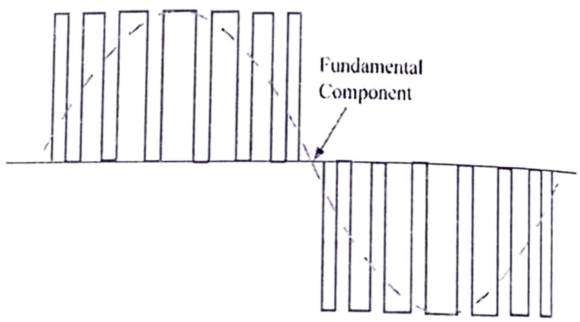


Fig. 14: Multiple Pulse Width Modulation: Sine Modulation

The PWM technique is divided into two major classes e.g. *Periodic Modulation* and *DC Level Modulation* (also known as 'on–off' modulation or variable duty-ratio modulation). Figures 15 and 16 depict schematics of periodic modulation. The PWM

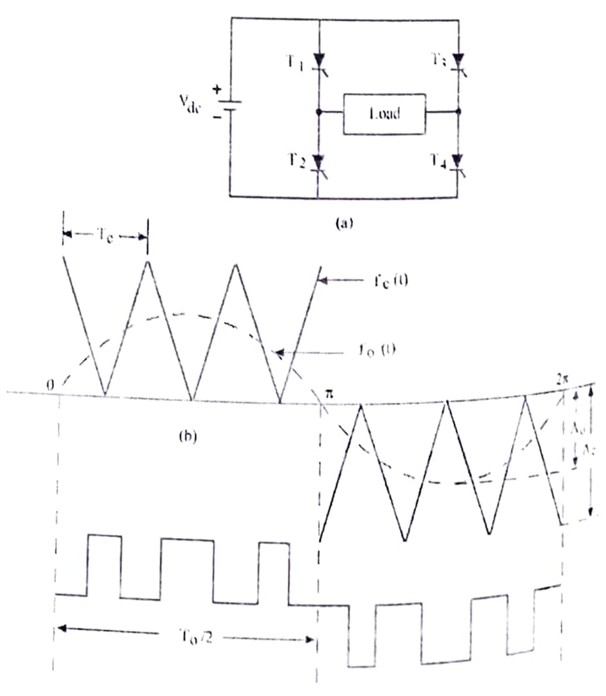


Fig. 15: Multiple Pulse Periodic Modulation

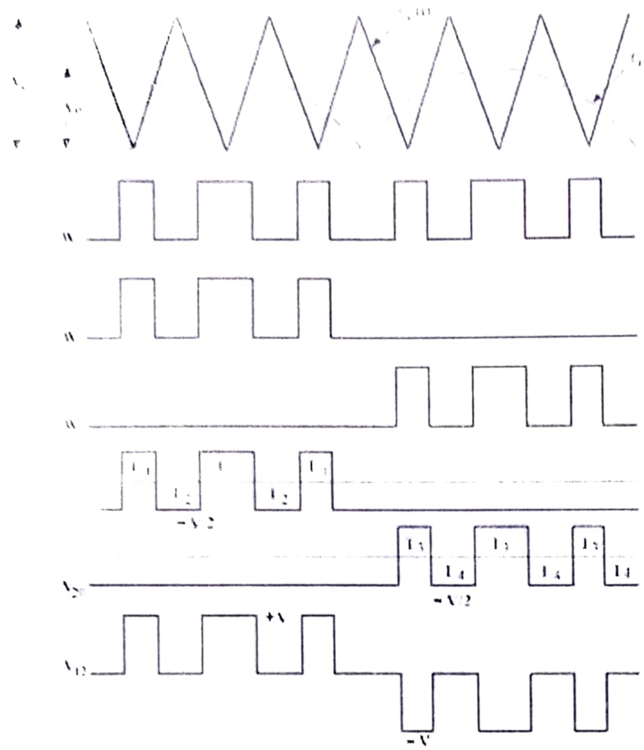


Fig. 16: Multiple Pulse Width Modulation

technique, in which the modulating signal is selected to be a periodic waveform, is known as Periodic Modulation.

As shown in Figures 15 the two signals i.e., the carrier and reference are compared and the crossing points of these are collected for the gating the PSDs.

These crossing points are also known as *firing coordinates*. While the control of output voltage is achieved through the *Modulation Index 'M'* which is the ratio of peak of *reference signal* to the peak of *carrier signal* (A_0/Ac); the control of output frequency is done through the *carrier ratio 'I'*. The ratio *'I'* is the ratio of carrier signal frequency to the reference signal frequency (f_c/f_0). Thus, by properly selecting the PWM control strategy the inverter output voltage and frequency can be controlled uniformly through a single converter control, unlike the conventional methods of Variable Voltage Input control (VVI) and Variable Voltage Output control (VVO) inverters and also the switching technique using the phase shift control [13,17,19,21,31].

1) *Periodic Modulation:* In this method the triangular carrier waveform is compared with a periodic modulating signal as shown in figure 15 and hence the crossing points of these two signals are determined as firing instants of the PSDs. As shown in the figure a rectified sine wave is selected as a reference signal, which is compared with the triangular carrier waveform. The crossing points thus obtained, are generated in the form of a pulse train 'W' as shown in the figure. This pulse train has been used to further generate two new pulse trains named as 'W_1' and 'W_2', which are 180^0 phase displaced from one another, to be used to fire the PSDs of the inverter 'limb 1' and 'limb 2' respectively, as shown in figure 15 (a). Thus, the pulse train W_1 generates the firing schedule for the inverter PSDs T_1 and T_2 and the train of pulses W_2 generate the firing of 'limb 2' PSDs T_3 and T_4. Therefore, as depicted in the figure the waveform 'V_{1O}' is the output voltage of the inverter 'limb 1' with respect to 'O' and similarly 'V_{2O}' is the output voltage of inverter 'limb 2' with respect to 'O'. As such, voltage across the load 'V_{12}' is the line-to-line voltage between 'limb 1' and 'limb 2' and is depicted in figure 16 by the waveform, 'V_{12}'.

The visual inspection of carrier and reference signals reveal that carrier frequency is three times the reference frequency. This means that the carrier ratio *'I'* should be equal to 3. A confirmation to this effect is revealed by figure 15 that there are three pulses per half cycle in the PWM output waveform.

2) *DC Level Modulation:* The DC level modulation also known by the names of 'On-Off' modulation and 'Variable Duty Ratio' modulation is achieved by comparing the DC level as a reference waveform with the triangular career waveform. Figure 17 depicts the DC level waveforms and its comparison with triangular signal to generate the modulated output. This output, which is a periodic waveform is although not a sine wave, but it is symmetrical and has lower harmonic content [17,21,31].

3) *Sinusoidal Pulse Width Modulation:* The PWM methods where a triangular wave is compared directly with a sinusoidal wave, so as to determine the switching instants of the power semiconductor devices is known as *Sinusoidal Pulse Width Modulation (SPWM)*, very often it is also called *Ideal Sinusoidal Pulse Width Modulation (ISPWM)*. The sinusoidal pulse width modulation technique is fairly well known and is a special case of periodic modulation, wherein the PWM output is obtained using a sinusoidal function as the modulating signal as shown in Figure 18. Since the reference signal is a sine wave, a marked reduction in harmonic content at the output of the inverter is achieved.

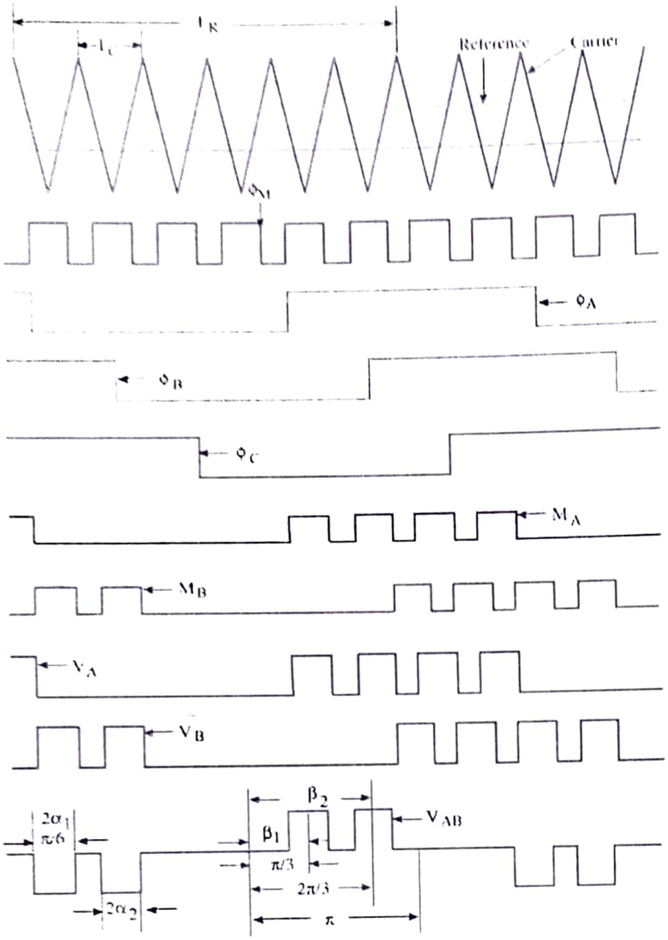


Fig. 17: Scheme for Variable Duty Ratio Modulation

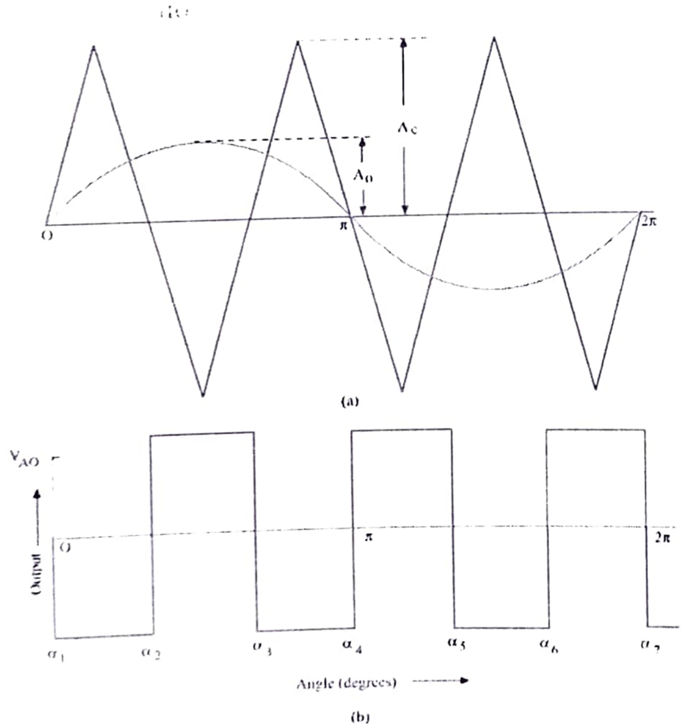


Fig. 18: Natural Sampling Technique

As shown in Figure 18, a triangular carrier signal is compared with a sinusoidal modulation waveform to determine the switching instants. This is also very often known as "*Naturally Sampled PWM Technique*". Since the switching edge of the width modulated pulse is determined by the instantaneous intersections of the two waveforms, the resultant pulse width is proportional to the amplitude of the modulating signal at the instant at which the switching occurs.

Since sinusoidal function is non-linear, the mathematical computation of firing coordinates becomes difficult in this case, due to the solution of a transcendental equation, which can only be solved using numerical technique. As such, *Natural Sampling (ISPWM)* cannot be implemented directly, except with those microcomputers, which have the powerful arithmetic capabilities to calculate the firing coordinates. An alternative approach therefore is to solve the transcendental equation through the main frame/desk top computer for the calculation of switching instants and thus store the results in a look-up table. Although, this method leads to the off-line control and results in a large storage memory for smooth control of voltage as well as frequency; the method is even then popular for low and medium power applications. Based on this strategy referred as earlier, a ROM based PWM inverter has been designed and built [17].

With the wide-spread availability of VLSIs, better PWM schemes and sampled PWM schemes like those using Marconi MA818 ASICS chips have become feasible [79,81,87]. Although, the strategy uses more involved hardware designs; these chips are more compact and reliable. Following are some of the points, which are worth noting:

- In the past, analog circuits have been used to generate sine waveform and compare it with the carrier, so as to generate firing coordinates for power semiconductor devices [31,38,76,78]. Three of such waveforms 120° displaced from one another were felt necessary for a three-phase inverter output. The amplitude of the output fundamental has been varied by varying the amplitude of the modulating signal (Sine Wave) as shown in figure 15 to vary the value of 'M'. However, varying the value of 'I' has made it necessary to vary the frequency. Both of these variations were conventionally done in the analog circuit [21,31].
- In order to avoid the complex method to generate sine wave a stepped or trapezoidal or some other

waveforms e.g., DC level modulation as shown in figure 17 are used. Otherwise the Sampled PWM technique as depicted in figures 19 to 20 have been more commonly practiced [42,47,54,58].

- Hybrid circuit schemes, where the firing coordinates are obtained by digital comparison of carrier and modulating signal have also been in practice in order to simplify the problem.

- The firing coordinates obtained in any of the above noted schemes can be computed a-priori. These firing sequences can be stored in look-up tables in 'ROM' to be accessed any time for the necessary control of voltage and frequency. Typical possible criterion used is elimination of a selected set of harmonics in the output, for a given application.

The last two methods are digital and are implemented with microprocessor based converter/ inverter systems only. These methods yield more precise harmonic elimination [40-42,49-53,55,58,59,62-66]. The last one calls for detailed computation at the design stage itself. But, undoubtedly it yields the best results. Specifically, with a given number of switching maximum harmonic elimination is achieved. However, the 3n+2 harmonics can be eliminated with n pulses per half cycle. In addition, the third and multiples of three harmonics will even then remain essentially ineffective in a three-phase system.

All of the above schemes have been studied in detail by various researchers and have been extensively investigated [64,66,67], keeping in mind the applications. Some papers have presented the efficient and reliable Genetic Algorithm based solution for Selective Harmonic Elimination (SHE) switching pattern [109]. Such methods are used to eliminate lower order line voltage harmonics in Pulse Width Modulation (PWM) inverter. Determination of pulse pattern for the elimination of some lower order harmonics of a PWM inverter necessitates solving a system of nonlinear transcendental equations. Genetic Algorithm is used to solve the nonlinear transcendental equations for PWM-SHE [109].

VI. FOURIER ANALYSIS OF THREE-PHASE PWM INVERTER USING SINE MODULATION

Referring to Figure 18, in order to analyze the wave shape of V_{AB}, the pole voltage waveform of one phase donated by V_{AO} is best to be analyzed. The waveform for pole voltage V_{AO} can be expressed in Fourier series form. It may be mentioned that calculation of the Fourier coefficients for PWM function is not straightforward. The angular positions of V_{AO} are dependent on the set values of the Modulation Index 'M' and the carrier ratio 'I'. These angular positions are known only if the points of intersection of carrier and sinusoidal functions are calculated by intersection technique. These coordinates are represented by $\alpha_1, \alpha_2, \ldots\ldots \alpha_{2i+1}$ as depicted in figure 16.

For odd values of *'I'* the waveform for V_{AO} has half wave symmetry. Therefore, for the odd values of carrier ratio even harmonics are absent. For even values of *'I'*, V_{AO} does not have the half wave symmetry. Even harmonics are therefore presented in V_{AO} and hence in the V_{AB} waveform, as shown in Figure 16. The V_{AO} can thus be expressed in Fourier series as:

$$V_{AO} = \Sigma_{n=1}^{\infty} A_n \sin(n\omega t) + \Sigma_{n=1}^{\infty} A_n \cos(n\omega t) \qquad (3)$$

Assuming that V = 1 per unit, from figure 16 we have;

$$B_n = 0.5/\pi\ [-\int_{\omega t_2}^{\omega t_1} \sin n\omega t\ d_{\omega t} + \int_{\omega t_2}^{\omega t_3} \sin n\omega t\ d\omega t$$
$$-\int_{\omega t_3}^{\omega t_4} \sin n\omega t\ d\omega t + \int_{\omega t_4}^{\omega t_5} \sin n\omega t\ d\omega t - \qquad (4)$$
$$\int_{\omega t_5}^{\omega t_6} \sin n\omega t\ d\omega t + \int_{\omega t_6}^{\omega t_7} \sin n\omega t\ d\omega t]$$

if $\omega t_i = \alpha_i$, for i = 1,2,........, 2I +1

$$B_n = 0.5/n\pi\ [-(\text{Cos}\ n\alpha_1 - \text{Cos}\ n\alpha_2) + (\text{Cos}\ n\alpha_2 - \text{Cos}\ n\alpha_3)$$
$$- (\text{Cos}\ n\alpha_3 - \text{Cos}\ n\alpha_4) + (\text{Cos}\ n\alpha_4 - \text{Cos}\ n\alpha_5) - (\text{Cos}\ n\alpha_5 - \text{Cos}\ n\alpha_6) + (\text{Cos}\ n\alpha_6 - \text{Cos}\ n\alpha_7)]$$
$$= 0.5/n\pi\ [-\text{Cos}\ n\alpha_1 - \text{Cos}\ n\alpha_7 - 2(\text{Cos}\ n\alpha_3 + \text{Cos}\ n\alpha_5) + 2(\text{Cos}\ n\alpha_2 + \text{Cos}\ n\alpha_4 + \text{Cos}\ n\alpha_6)] \qquad (5)$$

For the present case when the reference signal is synchronized with positive slope of the carrier $\text{Cos}\ n\alpha_1 = \text{Cos}\ n\alpha_7 = \text{Cos}\ n\alpha\ (2I + 1) = \text{Cos}\ 2\pi = 1$, therefore we have:

$$B_n = 1/n\pi\ \{\Sigma_{i=1}^{2I}\ i \cos n\ \alpha_i\} \qquad (6)$$

Similarly, it can be shown mathematically that;

$$A_n = 1/n\pi\ \{\Sigma_{i=1}^{2I}\ i \sin n\ \alpha_i\} \qquad (7)$$

Thus,

$$V_{AO(N)} = \sqrt{A_n^{Z} + B_n^{Z}}$$

A. *Computation of Points of Intersections*

Having completed the mathematical computation of the Fourier Coefficients, it is worthwhile to discuss the computation of firing coordinates. As mentioned earlier, the waveform for V_{AO} may or may not have half-wave symmetry. Therefore, coordinates for a complete cycle of the reference function are computed. In order to find the coordinates in complete cycle, the equations of carrier function should be known. Equation of the first line of carrier with positive slope that meets with zero crossing of modulating signal is given by:

$$Y = (Y_c . 6/\pi).X \qquad (8)$$

Where 'Y' is the variable for magnitude and 'X' is the variable for angular positions. Equation of second line of the carrier is therefore written as:

$$Y = - Y_c . 6/\pi(X-\pi/3) \qquad (9)$$

Equation of third line is;

$$Y = Y_c . 6/\pi(X-2\pi/3) \qquad (10)$$

In this way, equation of i^{th} line of the carrier can be written

$$Y = (2I. Y_c/\pi) (-1.0)^{i+1} (X-i-1. \pi/I) \qquad (11)$$

Where I = 1,2,3, ... 2I.

Each point of intersection, 'X' of carrier & modulating signal is given by:

$$Y_r . \text{Sin} = Y_c . 2I/\pi. S (X-i-1.\pi/I) \qquad (12)$$

Where $S = (-1.0)^{i+1}$. Thus on solving for 'X' we have:

$$X = (\pi/2I). M/S) \sin X + (i-1). (\pi/I) \qquad (13)$$

$$X = P. \text{Sin } X + Q \qquad (14)$$

Where, $P = (\pi/2I). (M/S)$

$Q = (i-1). (\pi/I)$

This is a transcendental equation and can be solved only by numerical method.

The value of 'X', for which equation (14) is satisfied to the closest approximation, is the point of intersection. In this way all points of intersections are computed and substituted in the expression for B_n and A_n given by equations (13 & 14). Values of A_n & B_n are substituted in the expression for V_{AO} computed in the preceding sub section.

B. *Limitations Of PWM*

Most of the off-line microcomputer based modulators have been developed principally on the look-up table technique, which hardly meets the requirement of practical variable speed drive (VSD) system. The number of notch i.e. 'angles for PWM wave pattern' tend to increase at lower fundamental frequencies, thus demanding large look-up table memory. Therefore, operation at lower fundamental frequencies and also the total number of wave patterns stored in the look-up tables becomes highly limited. Even if the memory size is considered to be no constraint, the hardware and software of the so far published modulator strategies are such that they often don't provide good angle resolution. The output waveform therefore does not respond accurately to the change in the inverter voltage and frequency commands. Further, a fully dedicated hardware control scheme requires complicated digital and analog circuit, often limited by the problem of 'drift'. Therefore, the present trend to use more of software and minimum hardware has made the computation of firing coordinates and their on-line implementation rather simple. Further, in order to obviate the solution of *transcendental equation* Sampled PWM as proposed is explained and discussed in the next sub section.

C. *Sampled Pulse Width Modulation*

Because of the limitations of analog circuits due to drift and aging; and also due to the difficulties of implementation of *ISPWM*, a new strategy known as *Sampled Pulse Width Modulation* using simple microprocessors has been proposed. The method though simple is somewhat approximate. Rather than using the sine wave for writing the mathematical expression, a sample and hold technique is used through which the sine wave is sampled at a specific point during the carrier wave and its value is held until the next cycle/half cycle. The firing coordinates are therefore computed by intersection of carrier and sampled signal rather than sinusoidal waveform. By doing so the solution of non-linear *Transcendental Equation* is avoided. As such, the on-line as well as off-line implementation of *Sampled PWM* has become very simple which can be handled by any microprocessor; thus obviating the need for solving the complex equation. The most commonly used Sampled PWM techniques are Regular Symmetric Sampling (RSS), Regular Asymmetric Sampling (RAS)

Modified Regular Sampling (MRS) and Modified Natural Sampling (MNS). These techniques are discussed in the following sub-section.

1) *Classification of Sampling Techniques*

In the Regular Sampling Technique the reference waveform is sampled and held at fixed points in every carrier cycle at regular intervals corresponding to the peak of the triangular carrier wave. The comparison of the sampled modulating wave with the carrier wave as shown in figure 19 generates the points of intersections, used to determine the switching instants of the width-modulated pulses. It may be mentioned that the sampled modulating signal has constant amplitude while each sample is being taken, and also the sampling points are regularly spaced. Consequently, the width of each pulse is proportional to the amplitude of the sampled modulating signal. The regular sampling technique is classified into two groups namely, *Regular Symmetrical Sampling (RSS)*, *Regular Asymmetrical Sampling (RAS)*. The case where the reference signal is sampled and held at every positive peak of the triangular wave, the technique is called Regular *Symmetrical Sampling (RSS)*, because the switching instants are symmetrical and equidistant from the point of sampling. In case the samples are taken at both positive as well as negative peaks of the carrier wave, the technique is called *Regular Asymmetrical Sampling (RAS)* as illustrated in figure 20. The computer analysis of the harmonic output of the two PWM techniques done in the laboratory demonstrates the improvement in the output waveform for *RAS* technique over the *RSS* technique.

Through yet another method known as *Modified Regular Sampling (MRS)*, the amplitude of modulating sine wave is stored by sample and hold circuit, at both positive as well as negative peaks of the carrier wave. The sine values of the two successive angles are then averaged to give new sample and hold modulating signal as shown in Figure 21. In this manner a better output with lesser harmonic distortion is obtained, but the limitation of this method is that the peak amplitude of a sampled modulating signal is lower than that of *Ideal Sinusoidal Pulse Width Modulation (ISPWM)*. This reduction in the amplitude of the sampled modulating signal causes significant reduction in the fundamental value of the output voltage [17,21,31]. Figure 21 gives the intersection points thus obtained in the *Regular Sampling* as well as in the *Modified Regular Sampling* techniques. It is clear from the visual inspection that the harmonic content in the output as compared to that of the *Natural Sampling* Technique is more in the case of Regular Symmetric Sampling.

Another improved version of the RAS is also purposed here. This technique is illustrated in Figure 22, where the existing RAS technique is modified by the linear optimization. By using the linear optimization of RAS in PWM inverters, a higher fundamental output and lower output harmonic distortion are obtainable [17,21,31]. However, the implementation of this method needs higher amount of calculation time, thereby limiting the speed of response, but it also allows the use of small and economical processors.

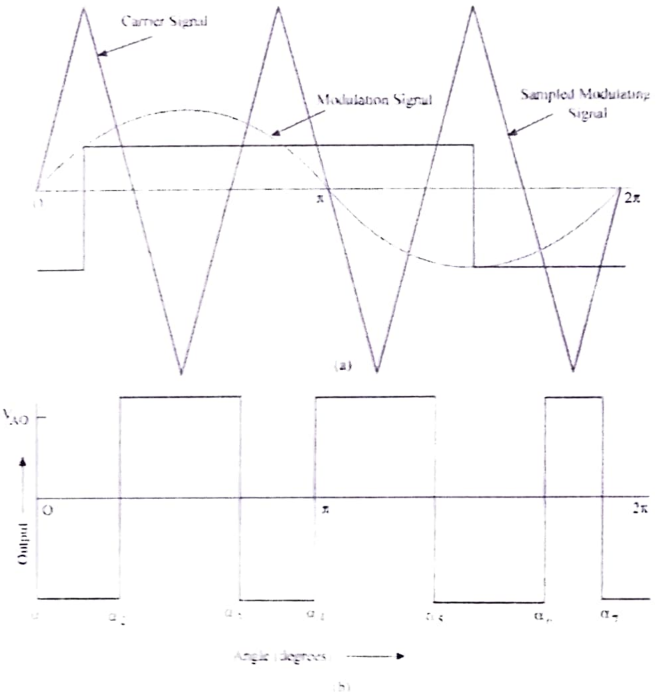


Fig. 19. Regular Symmetrical Sampling (RSS) Strategy

D. *Modified Natural Sampling*

A new method for microprocessor implementation of PWM technique called *Modified Natural Sampling* has been suggested by Bhatia et al [74,76] at *I.I.T Delhi*. In this new technique the sine waveform is sampled and stored. The comparison of the magnitude sine wave samples is next done with the positive and also negative slopes (ramp) of the triangular carrier wave as shown in figure 23. During either the positive or the negative slope profile the difference between the magnitudes of the ramp and sampled sine wave will have a definite sign. However, the sign of this difference in magnitude will change whenever the crossing of the two signals has taken place, as shown in figure 23. This change in sign brings in the crossing point subject to accuracy. This accuracy depends on the number of samples of sine wave taken per cycle; higher the samples better is the accuracy.

1) Generation of Sinusoidal Reference Signal

The generation of sinusoidal signal in the Modified Natural Sampling technique is done in such a way, that the requirements for the calculation of trigonometric functions as well as the floating-point arithmetic are bypassed [74,76]. For this purpose "k" samples of sine function from 0 to 360 degrees at regular intervals are stored in the sine table. Each data in the sine table is obtained by multiplication of the sine value at a particular instant by 100, so as to from an 8 bit data in the integer form. Further, the values of the modulation index M are converted into the integer from the same multiplication method. If the entire data of the sine table, one after the other, is multiplied by the required modulation index M, it is obvious that these values thus obtained can be used as per the unit values of the sinusoidal signal. It may be mentioned here that by changing the value of "M", the data thus obtained gets modified to represent different levels of the amplitude for sinusoidal waveform. Preceding in this manner it is possible to obtain the data required for the reference sinusoidal signal.

2) Generation of the Triangular Carrier Waveform

To generate a triangular carrier waveform through the software, it is sufficient to generate a ramp function of the following form;

$$F(x) = X + F(X-1) \text{ for positive slope}$$
$$F(x) = -X + F(X-1) \text{ for negative slope} \quad (15)$$

Where, F(x) is the current value of the ramp function, and F(x-1) is the previous value of the ramp function.

Generation of such a function using the microprocessor is very simple, because it is sufficient to add '1' unit to the existing initial value of the ramp function during the positive slope; and subtract '1' unit from the existing initial value, for generating the ramp with negative slope.

The newly suggested method as explained in Figure 23 is very simple. Since the mathematical model of the process is very simple, this enables the designer to calculate the firing coordinates more accurately [74,76]. The number of samples of sine wave determines the accuracy of this technique. The generation of software of this technique is very simple and requires simple as well as low cost processor for its implementation.

The accuracy of the proposed method is highly dependent upon the number of samples chosen per cycle. Figure 23 shows the extent of error caused due to shift in the crossing point in Modified Natural Sampling as compared to the ISPWM method. This shift depends on the number of samples taken. Higher the number of samples per cycle lower is the error.

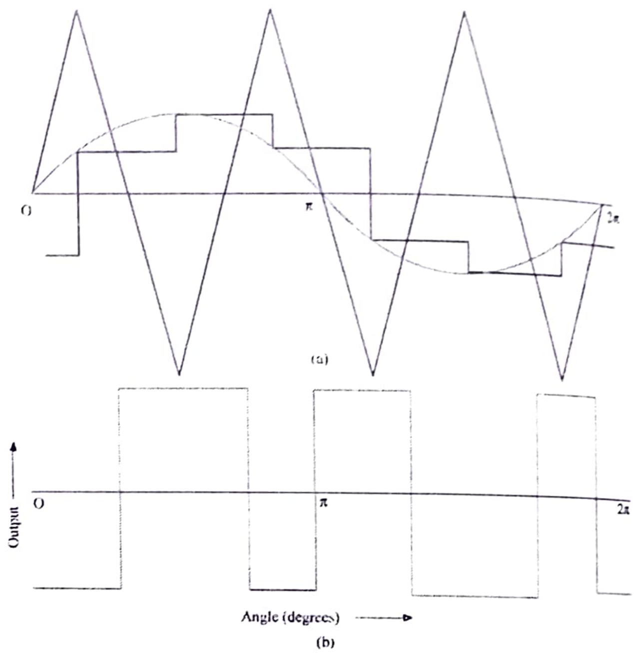


Fig. 20. Regular Asymmetric Sampling (RAS) Technique

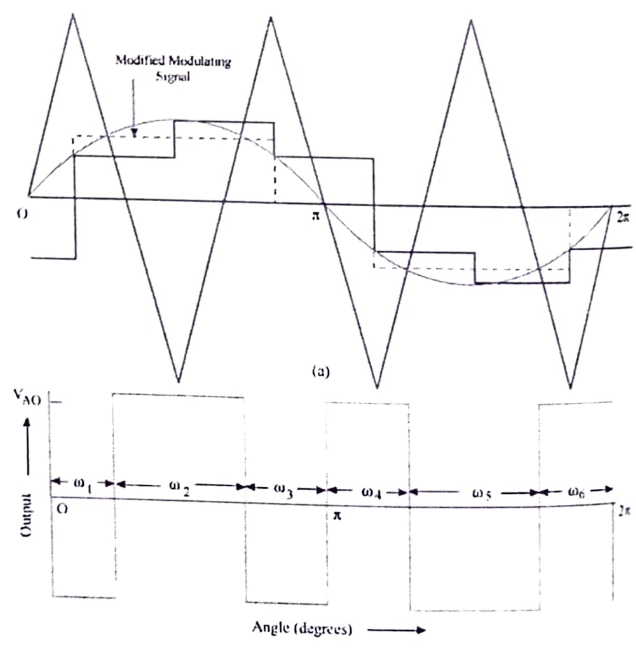


Fig. 21: Modified Regular Sampling (MRS) Technique

E. Comparison of Sampling Methods

A vivid comparison of harmonic contents in the output voltages as obtainable from various sampled PWM methods e.g., Regular Symmetrical Sampling, Regular Asymmetrical Sampling, Modified Regular

Sampling, and Modified Natural Sampling (MNS) with the ideal Sinusoidal Pulse Width Modulation (ISPWM) is given in [74] for various values of modulation index 'M' and carrier ratio 'I'. It is noted that the MNS technique suggested by Bhatia et al [74] has the minimum harmonic content in the output and delivers higher value of the fundamental voltage. For further details on MNS technique reference may be made to [74,76].

Having completed the description of inverters and control techniques, it is worthwhile to review application of these circuits and systems for the speed control of AC drives. One of the most popular and widely applicable AC drives is the induction motor.

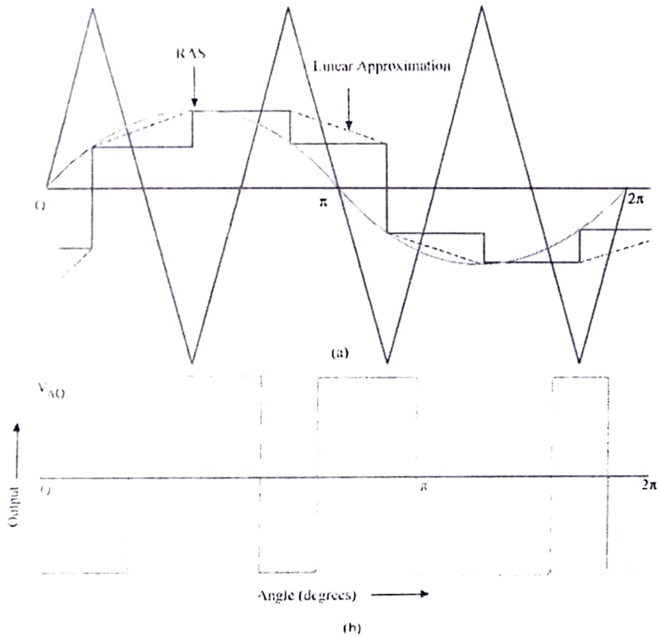


Fig. 22: Linear Approximation Technique

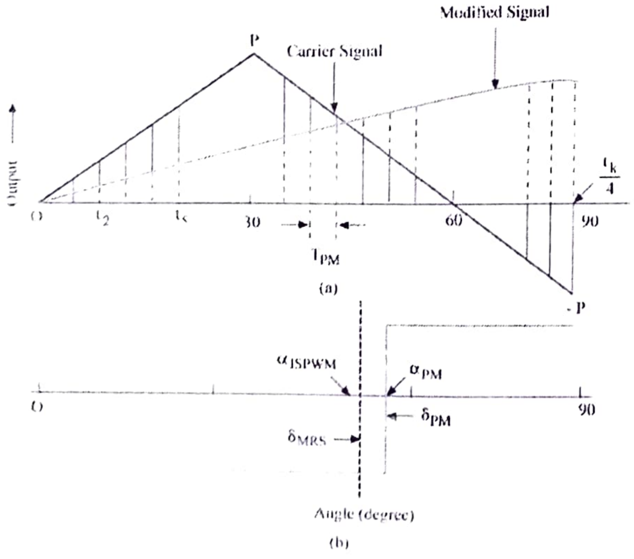


Fig. 23: Modified Natural Sampling (MNS) Technique

VII. FUNCTIONAL CONTROL OF PWM DRIVES

In this section a comprehensive review is presented about functional control of drives. As mentioned earlier in this research paper, basically two major control functions are called for, namely:

- Control of voltage applied to the motor
- Control of frequency.

For the present, it is worthwhile to confine to PWM inverter schemes described so far, for the Fault Mode Analysis and Knowledge Based Protection System for Inverters [101,105,106,110].

Depending on the power level of the drive and its versatility different types of circuit scheme are suggested [111]. Figure 24 shows a possible circuit scheme in simplified form, using analog circuit building blocks. The set speed command is used to decide the magnitude and frequency of the modulating signal. The same is used to decide the frequency of the carrier signal. Similar modulating and carrier signals are generated for the three-phases [21]. During the past, these signals have been combined through the comparator and logic circuits to generate the firing coordinate to fire the main PSDs of PWM inverter [17,21,31].

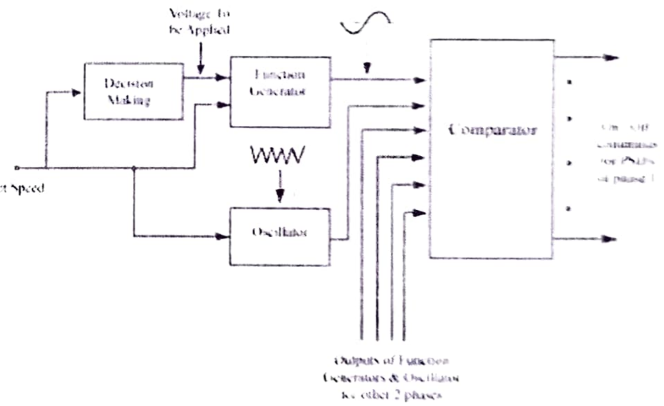


Fig. 24: Control for Analog Based PWM Technique

These schemes use elaborate analog circuitry and are more or less inflexible. All functions have to be planned in advance and need to be thoughtfully built in. Although, the result of this PWM system is much better than the six-step inverter, it yields poor efficiency. The harmonics content can be reduced further by several other schemes, which are more flexible and easy to operate.

A variety of digital schemes are possible. Earlier PWM schemes implemented the system of figure 24 into digital form. This was accomplished by generating stepped waveforms similar to the carrier and modulating signal and subsequently comparing them. It does simplify circuit compared to a scheme based totally on discrete components. ASICS chips e.g., MA818 etc., have been extensively used and many drives in past have been build using these IC. However, performance wise, these are only marginally better. The PWM schemes discussed as above are frozen for a sinusoidal case e.g. MA 818 system [78,80,86]. Though, the harmonics are reduced considerably, the large number of switching operations of PSD thus done incur higher switching losses and therefore reduce the drive efficiency considerably.

As shown in Figure 25, more recent schemes use a radical approach to design. The firing coordinates corresponding to the intersection of carrier and modulating signal are computed and tabulated in the form of look-up tables [17] for various modulation indices 'M' and carrier ratios 'I'. The tables can be stored in digital memory e.g. ROM, which is accessed using either an off-line control or an on-line control through either manual settings or through a microcomputer [76,78]

The microcomputer can accept the set speed input; decide on the frequency ratio and modulation index to be used. It next steers operation to the corresponding table switching angles in memory [76]. Once again, implementation can be brought about in a variety of ways. Figure 25 shows a practical scheme designed developed and built at IIT Delhi [17].

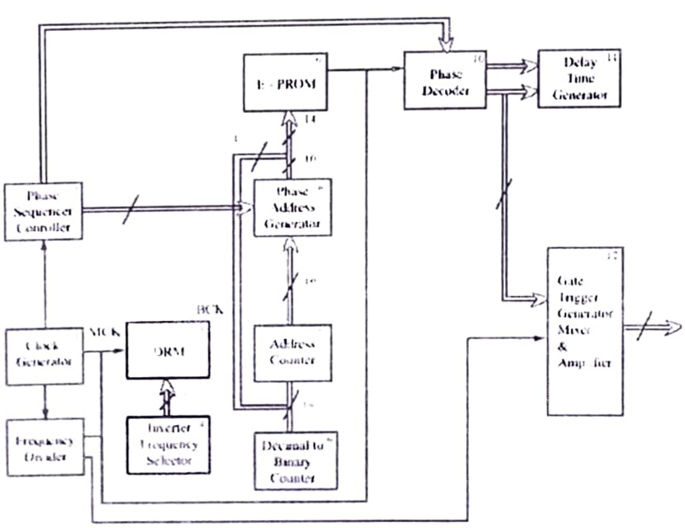


Fig. 25: ROM based PWM AC Drive System

In case the circuit of figure 25 uses the microprocessor, the microprocessor has a variety of co-ordination functions to do and to make allied decisions [76,78]. Its key functions are:

- Accept the parameters e.g., set frequency command, upper load limit, acceleration time etc.
- Compute the output voltage required and identify the modulation index required from the above and hence the DC link voltage.
- Select the page of switching angles to be used, and communicate the same to the command generator block.
- Accept user commands and take follow-up action.
- Do all protection functions related to the motor and the inverter.
- Do all display and annunciation related functions.

VIII. EXISTING PROTECTION SCHEMES

In this section a case study is presented on protection aspect of drive [77,110]. The basic protection offered by AC drives is broadly of three types –

- Inverter/Converter related.
- Motor related.
- Load related.

Mechanical stresses, process requirements etc., may require the drive to accelerate and/or decelerate at specified rates. These are normally ensured by the drive by changing the supply frequency at a predetermined rate. Upper load limit may have to be limited at a specified value. Identifying the corresponding maximum load current through the motor and keeping it within the identified limit generally does this job. In short, the load related protection features are acceleration and deceleration rates that limit upper load magnitude [77,86,88].

Motor related protection features are well established.

- Thermal protection is executed by realizing inverse time current curve. Many of the modern drives systems realize this in the software and do not use a separate thermal overload relay.
- Overload (current) protection is generally realized by comparing the load current with a set upper limit and taking protection action.

- Upper speed limit set is also the load-related protection. It is realized by the drive not accepting set speed above the specified limit.
- Supply voltage to the motor is limited to avoid over fluxing and related insulation problems.
- Unbalance in motor line currents is kept in check. In comparatively high power drives, larger than 100 HP or so, this is realized by computing the negative sequence component of current and keeping it within limits. In smaller drives this aspect is done in an indirect manner by. checking the ripple current level on the DC link.
- Under voltage protection is done by comparing DC link voltage against a lower set limit and taking necessary protection action to realize function.
- Earth leakage protection is not provided in small drives. But, as the power capacity increases say beyond 50 HP, it becomes necessary. This is realized with the provision of an earth leakage relay.

It is therefore expected that a well-designed and engineered drive would ideally be fool-proof [77] and does not require protection any further. Such an approach to drive has been adopted by very few limited manufactures. However, almost all manufacturers treat the above as a hypothetical phenomenon and have minimum necessary protection circuitry. The following are the commonly built-in protective features:

- Short circuit protection for the PSD: This is built in as part of the base/gate drive of PSD. The PSD is turned off on short circuit.
- Thermal protection for the PSD: The heat sink temperature is measured & in case it exceeds an upper set limit, the drive is switched off.
- Protection against unequal voltage distribution in filter capacitors: DC link filter capacitor bank comprises of a number of capacitors. Any unbalance in voltage distribution is hazardous to the capacitor and hence it should be avoided.
- Fast acting semiconductor fuses in DC link and AC supply line provide short circuit protection at the respective points.
- DC link over voltage protection: This is necessary to avoid overstressing of PSDs [101].
- Watchdog protection for the microprocessor: In case of microprocessor failure, the drive operation can get paralyzed. To avoid this eventually, the watchdog keeps a close watch on the microprocessor. In case of its failure, the watchdog circuit gives out an alarm or enables a contact or relay, which can be used to initiate emergency follow up. The watchdog circuit also shuts down the PSDs, Contactors, etc. In case of over voltage, the main contactor of the drive may be turned off to protect all the rest of the devices. In all other cases the PSDs may be turned off and the contactor left undisturbed.

Protection is realized at various levels [86,98,101,110]. All load and motor related protection activities can do with protection through the microprocessor. The protection signal interrupts the processor and seeks action. The associated delay will be of the order of a few microseconds. This delay is within the tolerable limits of the drive. In contrast, the drive related protection has to be faster [86,110]. For example, over current/short circuit protection for the PSD has to act within a microsecond. In these cases separate protection hardware is built-in. Very often after initiating the protection action locally, these inform the processor of the same. The processor may disable the drive completely. Operation is resumed after operator clears the fault and the processor is informed of the same through a reset signal.

IX. USER INTERFACE AND DISPLAYS

Displays serve the following two functions:

- To provide information to the user on specific values of drive parameters and to indicate the drive status. Motor voltage, load current, power input to the drive, set speed, etc., are of the former category. A single 7 segment or a dot matrix based display can serve the purpose.
- User can select the specific variables to be displayed [77]. This makes the display compact as well as elegant. However, operating personnel are used to separate analog meter displays for current, voltage, frequency, etc. Hence, some drives provide separate panel meters for this purpose. This practice is more prevalent at higher power levels. Sophisticated drives may have the provision to transmit these parameter values to a remote location on a serial link.

Drive status indication can comprise of a number of simple LEDs [77]. Typical of such indications are:

- Mode identification – Whether RUN mode, Program mode, etc.
- Status indication – Running, Reset, Tripped etc.

- Forward/Reverse direction of rotation indication.
- Type of control – Local or Remote.
- Type of running – running at normal speed, jogging or inching, etc.

Drive status indication serves the additional purpose of diagnosis of faults. All out of the way operating conditions are indicated for this purpose. Separate LEDs may be provided for each. Typical indications are for Overload, Short circuit, Thermal trip & Capacitor voltage unbalance. A variety of other such indications are also possible.

Any drive requires and also offers the minimal control facilities for operations e.g. 'on', 'off', 'reset' and 'speed set' functions. Beyond these, a variety of such operations is possible and available. Comparatively earlier versions have separate provision for adjustment of each of the parameters (apart from speed) like load limit, upper and lower speed limits, acceleration and deceleration times etc. [77,101].

In more recent design of drives all such parameters are made programmable. Programming is done through a well-designed keyboard or thumbwheel switches. For sectional drives and high-end versions, programming can be done by a detachable keyboard or through a PC. Different lockout facilities are also inherent in these. Thus, in the most versatile mode, all parameter may be accessible for reading as well as adjustment. This mode is involved during commissioning or plant tuning. Once the parameters are set to meet the requirements, supervisory personnel may retain them. At the other extreme end, the drive may have a 'run' mode with minimum user interaction. 'On', 'off' and 'reset' switches alone may be active in this case. If a bit more of user interaction is desired, one can have a 'Speed mode' where the user adjusts the set speed also in addition to the basic 'on/off' controls above [77].

A. *The Intelligent Drives*

The presence of microprocessors makes it possible to build a certain level of intelligence to the drive control [83,105,106,110]. This takes a variety of forms. Typical of these are the self-diagnostics. The microcomputer goes through a self-check routine on energizing it [83,106]. This involves checking memory elements, health of contactors, parameter values and ensuring they are within set limits. In case of an abnormality, further systems operation may be stalled.

Programmability: Facility for the user to set parameter values and checking that the set values are within allowable limits constitute programmability. The drive also may have the facility to adjust some motor-dependent parameters such as IR drop compensation, slip compensation, etc.

Menu Driven Interface: Large variety of features and adjustments can confuse the user. Therefore, good drives ensure user-friendliness in a variety of ways. One effective method is to tie-up the display to the keyboard in an interactive manner and provide a lead to the user – for his next response. The user can proceed with setting the drive and using it without the help of elaborate instruction manuals.

Serial Interface: A series interface opens up a variety of possibilities. Operation can be monitored by a remote master computer. Choice between local & remote set values can be user-definable. Sectional drives, which use a number of motors in tandem can be effectively put together or regrouped. Motor and drive operations can be logged at the desired locations.

X. CONCLUSIONS

This paper presented a comprehensive survey of the Variable Speed Drive mainly the squirrel-cage rotor induction motor drives, its basic requirements and inverter control strategies as available in the published literature. The paper also reviewed various control methodologies especially the PWM inverters, harmonic elimination techniques and new PWM strategy namely the Modified Natural Sampling [50-52,54-55,58-67,70-79,81,111].

Most of the power electronic drive systems with converter/inverter operate in an environment requiring rapid speed variation, frequent start, stop and continuous overloading. The circuits and systems are therefore subject to constant abuse of over-current surges and over voltages. Although, conventional protection devices and circuits with current limiting fuses are commonly used; it is worthwhile to mention that switching devices are physically small and thermally fragile as compared to the power apparatus and systems that they control. Even a small electrical disturbance can cause their thermal rating to be exceeded, resulting in rapid destruction. In many cases, occasional failures may be tolerated; but in applications where expensive, high power systems are involved, knowledge based systems with intelligent control are demanded, which may be required to protect sudden system failure.

This review paper has therefore summarized the subject of variable speed drives with both aspects e.g., PWM control and the intelligent control with knowledge and information about the fault behavior of power electronic circuits. Both of these aspects being important, further research work on protection and fault tolerant control is in progress. It is hoped that work on condition monitoring and fault diagnostics of motor will receive attention by application engineers.

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