멀티레벨 인버터와 다상 유도기를 이용한 견인기용 대전력 VSI의 구조와 특성

K. Gopakumar* 류홍제** 김종수** 임근희**
* Indian Institute of Science, INDIA ** 한국전기연구소

Configurations of High Power VSI Drives for Traction Applications Using Multi Level Inverters and Multi Phase Induction Motors

Abstract - Current source inverter drives of auto sequentially commutated type are very popular in high power applications, because of simple power circuit configuration with four quadrant operation. But the six-step current output create harmonic problems and the input power factor of such a drive is not always good. In this respect pulse width modulated drives using gate turn off thyristors (GTO) are finding application, especially in traction drives. However the switching and snubber loses of a GTO do not permit the inverter switching frequency go beyond a few hundred hertz.This will again introduce low frequency harmonic problems. Multi level inverters of the 3-level and 5-level can be considered as an alternative to overcome the low switching frequency harmonic problem of the 2-level GTO inverters. But with multi level inverters the complexity of the power circuit increases. In this paper a combination of multi level (2-level and 3-level) inverters and multi phase induction motor (3-phase and 6-phase) configurations are presented for high power VSI drives for traction applications with reduced inverter switching frequency requirements coupled with reduced voltage rating for the power switch.

1. Introduction

Conventional current source inverter fed synchronous motor drives are used in high power variable speed drives for pumps, compressors etc,. The main disadvantage of the conventional CSI configuration is the need for bulky DC link inductors in the power circuit. Moreover the six-step output current waveform produces sixth harmonic torque oscillation problems, especially at low speeds of operation. The cancellation of the sixth harmonic problem can be achieved in induction motor drives by using six phse motor and dual CSI power circuit [1].[2]. But these type of drives are seldom preferred in high speed drives, requiring high dynamic performance as well. Pulse width modulated (PWM) GTO inverters are being increasingly considered for such applications, up to a certain power level only. A GTO based inverter can switch up to a maximum switching frequency range of typically between 300Hz to 500Hz. This can also lead to harmonic problems in variable speed drives, especially at low speeds. This will call for a high frequency PWM operation, which will result in high inverter switching loses, at high power levels. A possible alternative to avoid high inverter switching frequency is to go for multi level inverters with 3-level and 5-level structure [3] [4]. Multi level inverters, especially 3-level GTO based inverters are being considered for traction drive applications. In this paper inverter drive configurations with 2-level and 3-level structure feeding 3-phase and 6-phase induction motors are proposed for high speed traction applications. GTOs with existing switching frequency limit are only required for the proposed power circuit configurations. A space phasor based PWM approach is followed for the comparative study of various power circuit configurations, presented in this paper. Multilevel inverters with open end winding for the induction motor, with phase shifted triangular wave forms, have been proposed by Stemmler and Guggenbach [5]. This has the disadvantage of unequal load sharing between inverters, especially at the upper speed ranges. But with the configurations proposed in this paper, equal load sharing of inverters can always be achieved, with appropriate voltage space phasor combinations from individual inverters.

2. Voltage space phasors: 2-level and 3-level inverters

The power circuit schematic of a 2-level 3-phase inverter is shown in Fig.1a. The voltage space phasors possible from this is shown in Fig.1b. There are a total of seven voltage space phasor locations possible in this configuration. A combination of switching states (+ - -) implies that top switch of phase-A and bottom switches of phase-B and Phase-C are on. A reference voltage space phasor with an average circular trajectory, having a maximum radius of $0.866V_{DC}$ (V_{DC} - DC link voltage) is possible using space phasor based PWM technique[6] [7]. This will result in a maximum phase peak amplitude of $0.577V_{DC}$, while still being in modulation. If the speed range is extended to six-step operation, a maximum phase peak fundamental amplitude of $0.637V_{DC}$ is possible with the disadvantage of higher fifth and seventh harmonics (nearly 20% of the fundamental). These harmonics can be suppressed using 3-level inverters. Fig.2a shows the power circuit schematic of a 3-level inverter and Fig.2b shows the voltage space phasor locations. There are a total of 19 space phasor locations possible as compared to 7 locations in 2-level inverters. So for the same reference vector , a lesser harmonic content can be achieved by PWM technique, with inverter output voltage vectors, close to the reference vector, forming a triangular sector, using volt-sec balance [6] [7].So for the same out put harmonic profile, a lesser switching frequency for the PWM inverter can be achieved, using 3-level inverter when compared to a 2-level inverter. For the 3-level in the 12-step mode operation the fifth and seventh harmonic content is much reduced, when compared to the six-step mode operation of the 2-level inverter. The same voltage space phasor structure (3-level inverter) can be achieved by using two 2-level inverters with open ending (neutral is disconnected) winding for the induction motor.

3. 2-level inverter with open end winding for the induction motor

The power circuit schematic of two 2-level inverter feeding a 3-phase induction motor with neutral disconnected, is shown in Fig.3a. The voltage space phasor structure for this configuration is the same as that of a 3-level inverter (Fig.3b). The DC link voltage requirement is only half to that of a 3-level inverter, with lesser circuit complexity and lesser number of power switch component. For the same voltage space phasor location more number of out put voltage vector combination is possible, (A total of 64 space phasor combination is possible, as compared to 21 from 3-level inverter), from the open end winding drive configuration (Fig.3b). So using appropriate space phasor combinations, from individual inverters, a PWM scheme with reduced switching loses can be arrived at, when compared to the 3-level inverter, for the 2-level inverter with open end winding for the motor. But the third harmonic current flow resulting from this has to be suppressed using harmonic filters [8]. But the harmonic filter is an expensive proposition, and the requirement of a third harmonic filter can be avoided if we use a 3-level inverter with open end winding, instead of a 2-level inverter.

4. Combination of 3-level and 2-level inverter with open end winding for the induction motor

The power circuit schematic for the 3-level and a 2-level inverter with open end winding for the induction motor is shown in Fig.4a. Fig.4b shows the voltage space phasors from individual inverter and Fig.4c shows the resultant voltage space phasor combinations from the two inverters. There are a total of (21×8) 168 voltage space phasor combinations possible from this drive configuration (Fig.4a). Thus with more inner triangular vectors a voltage space phasor based PWM scheme with lesser inverter switching frequency is possible with this scheme compared to the previous schemes presented in this paper. Here the third harmonic content is much less and correspondingly , the harmonic filter size and cost can be reduced. The third harmonic content can be further reduced if both the inverters are of 3-level type. With two three level inverters a total of 441 space phasor combination is possible with the same resultant voltage space phasor locations. Among the various space phasor combinations, a certain combination can be used for total third harmonic elimination (Fig.4d). From Fig.4d, it can be verified that the fundamental phase peak maximum is reduced, when third harmonic elimination combination

(Voltage space phasors from individual inverters) is used for PWM operation. A further increase in fundamental phase peak maximum is possible(With a DC link voltage of 1/4 V_{DC}) , with a six phase induction motor drive.

5. Six phase induction motor drive

The schematic of a six phase induction motor drive is shown in Fig 5a. Fig.5b. shows the stator phasor diagram There are two sets of three phase groups namely ABC and A' B' C' . The two sets are separated with a 30 electrical degree angular separation. This can be easily achieved by splitting the phase belts of a conventional three phase squirrel cage induction motor into two equal halves with a 30 electrical degree of angular separation

[7] [9]. Fig.6 shows the voltage space phasor combinations from individual inverters which are switched with a 30^0 phase shift. The extreme boundary of the voltage space phasor combinations from individual inverters form a 12 sided polygon. Using space phasor based PWM technique, the maximum radius for the average circular trajectory for the reference space phasor, is $0.9659V_{DC}$ (V_{DC} $\cos 15^0$) [7]. So the maximum phase peak fundamental, achievable from space phasor based PWM, is $0.643V_{DC}$ (2/3 $0.9659V_{DC}$), which more than that of a six -step waveform($0.63V_{DC}$)[7]. So if the modulation is extended to 12 step operation more fundamental phase peak amplitude is possible, with a reduced DC link voltage ($0.5V_{DC}$), when compared to a three phase drive. But for a six phase machine the fifth and seventh harmonics are zero sequence components and hence will not contribute to the air gap flux [7]. The amplitudes of fifth and seventh harmonic currents are limited by stator impedance only, and hence large amplitude fifth and seventh harmonic current can flow in the stator, resulting in stator copper loses[7] [8] [10]. These harmonics can be suppressed by harmonic filters

[9] or appropriate space phasor based PWM technique [7] [9].

Inverter drive configurations using six phase induction motor drive with open end winding can also be considered for high power inverter drive applications. Fig.7a shows the block schematic of such a drive using four 2-level inverters with only 1/4 V_{DC} DC link voltage, where V_{DC} is the equivalent DC link voltage for the three phase system. Since only low DC link voltage is required, such schemes can be made using low voltage GTO switches. Moreover the reliability of such a system is more than that of a conventional drive. More space phasor combinations from individual phase group is available for space phasor based PWM technique, resulting in an equivalent 3-phase 24-stepped output waveform, with much reduced 3^{rd} ,5^{th} and 7^{th} harmonic contents.(Fig.7b.) Instead of 2-level inverters, if we use a 3-level inverter (Fig8a.), the number of space phasor combinations is much more (Fig.8b.), and correspondingly an equivalent 3-phse fundamental of 48-stepped output wave form is possible at the extreme end of PWM operation as compared to six-step in a conventional drive. This will result in much more reduced zero sequence components, in the stator circuit, which can be eliminated using either PWM technique [.7.] [9], or by magnetic leakage coupling in the machine end winding itself [10], or by harmonic filters[9].

6. Conclusion

In this paper a combination of multi level and multi phase induction motor configurations are proposed for high power traction applications. The voltage space phasor structure arising from this configuration is highlighted for 3-phase and 6-phase machines driven from 2 level and 3 level inverters. As the space phasor combinations increase with open end winding structure, an induction motor drive with reduced switching frequency and with half the DC link voltage of a conventional drive, is only required for the same power output. With the six phase induction machine drive , the requirement of the DC link voltage is only one fourth (1/4 V_{DC}) to that of a conventional 3-phase drive for the same power output. But in six phase machine drive the zero sequence components such as 3rd, 5th, 7th order harmonics has to be suppressed. This can achieved either by harmonic filters or by appropriate switching vector combinations from individual inverters for space phasor based PWM. For the six phase induction motor drive with open end winding structure, each inverter has to be switched only at 1/4 th switching frequency with only 1/4 th DC link voltage, when compared to a conventional 3-phase drive. So this scheme can be considered for high power inverter traction drive applications, where a GTO based inverter need to be switched at low switching frequency (typically 250Hz) and the motor control (PWM control) of flux and torque will be at high switching frequency (typically 1khz), with 1/4 th DC link voltage. This will result in reduced switching loses for the inverter and increased overall efficiency for the drive system.

7. References

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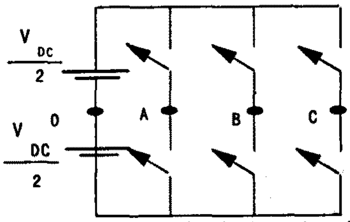


Fig.1a - Schematic of a three phase inverter

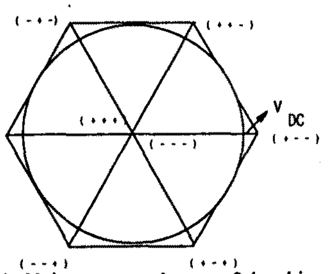


Fig1b. Voltage space phasors - 2-level inverter

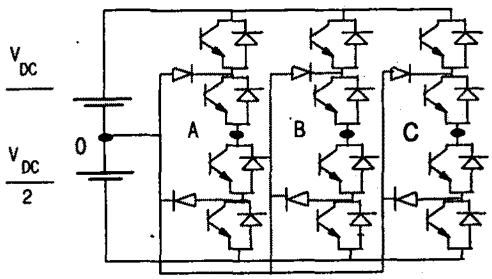


Fig. 2a - Schematic of a 3 - level inverter

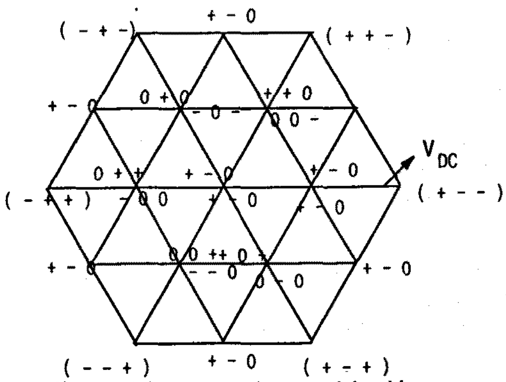


Fig. 2b. Voltage space phasors - 3-level inverter

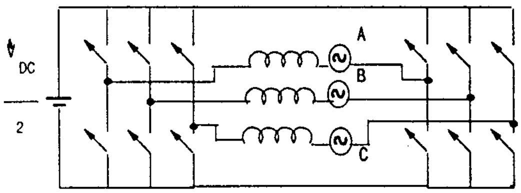
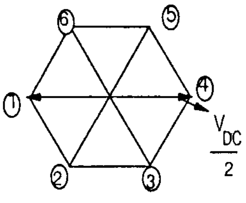
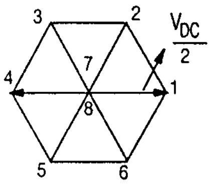


Fig.3a - 3- phase motor with open end winding driven from two 2- level inverters.



Inverter - 2

Voltage space phasors Inverter - 2



Inverter - 1

Voltage space phasors Inverter -1

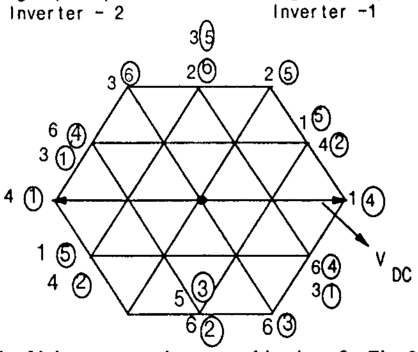


Fig. 3b - Voltage space phasor combinations for Fig. 3a.

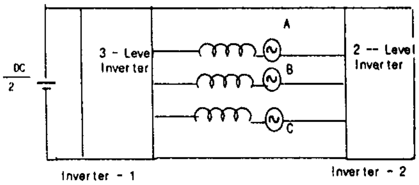
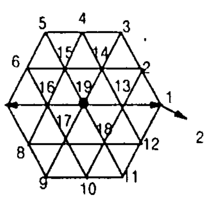


Fig.4a - 3- phase motor with open end winding driven from 3 - level and 2 -level inverters



ig. 4b Voltage space phasors 3- Level Inverter

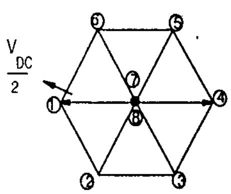


Fig.4b Voltage space phasors - 2 - Level Inverter

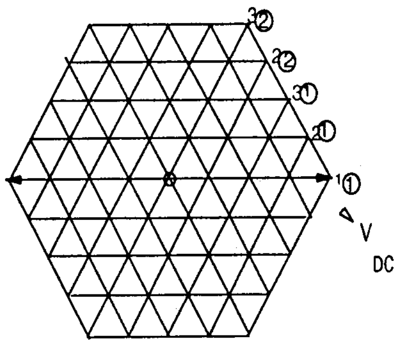


Fig. 4c - Voltage space phasor combinations for Fig. 4a.

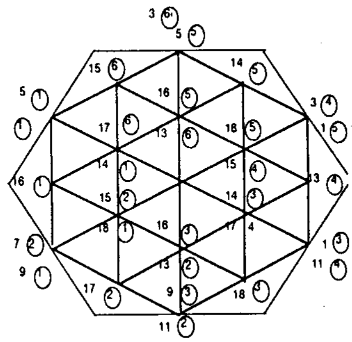


Fig. 4d - Voltage space phasor combinations from Fig. 4a. for third harmonic cancellation

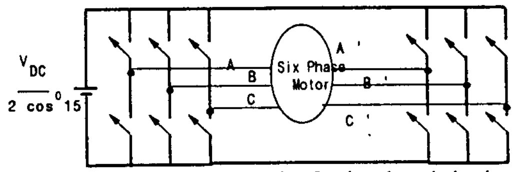


Fig. 5a - Power circuit schematic of a six -phase induction motor drive.

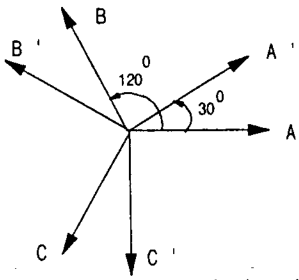


Fig. 5b - Phasor diagram -six phase drive

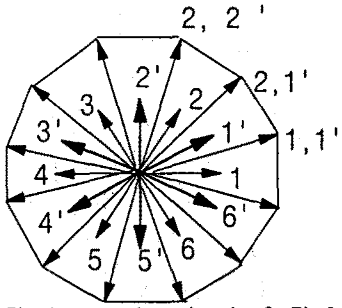


Fig. 6 - space phasor location fo Fig.5a

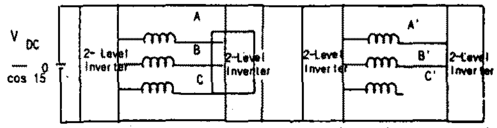


Fig. 7a - Six phase induction motor drive with open end winding fed by four 2-level inverters

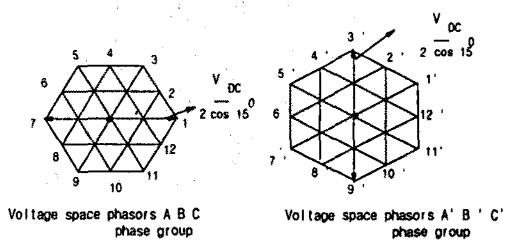


Fig. 7b

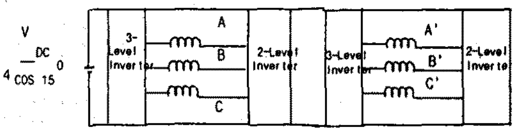


Fig. 8a - Six phase induction motor drive fed by two 2-level inverters and two 3- level inverters

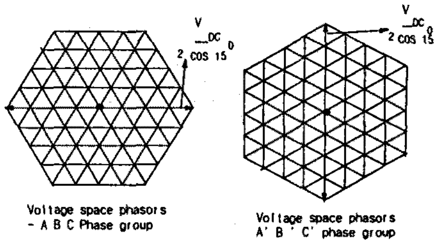


Fig. 8b