AN EFFICIENT PWM TECHNIQUE FOR SPLIT PHASE INDUCTION MOTOR OPERATION USING DUAL VOLTAGE SOURCE INVERTERS

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ABSTRACT

Split phase induction motor operation from dual PWM voltage source inverters offers the advantage of reduced voltage rating for the inverter devices. In addition, a total of 49 different locations are possible for the resultant stator voltage space phasor. The outermost locations form a twelve sided polygon. By space phasor PWM generation based on the vertices of the twelve sided polygon, a higher range of fundamental motor voltage is possible in the modulation range, up to $0.643 V_{DC}$, where V_{DC} is the DC link voltage for an equivalent 3 phase inverter, as compared to $0.577 V_{DC}$ for the three phase motor. This is brought about by the presence of 5th and 7th harmonics in the average polar voltage waveform. These harmonics get eliminated in the air gap mmf because of the winding disposition. However, they cause stator currents to flow and these currents are limited only by the stator leakage impedance. At low speeds, these currents can be very high. In this paper a PWM strategy is proposed for a split phase induction motor drive, wherein at low speeds each of the inverters is operated with conventional three phase space phasor modulation, thereby avoiding 5th and 7th harmonics in the motor voltage. At the higher end of the speed range a voltage space phasor modulation based on the twelve sided polygonal vertices is used, so that the benefit of a higher speed in the modulation range is retained. A technique for achieving the transition to that range without current transients is proposed. The scheme is verified through computer simulation, using a space phasor based model of the split phase motor. Details of a practical control circuit for voltage space phasor based PWM pulse generation are presented and the results from an experimental drive are highlighted.

1. INTRODUCTION

When the phase belts of a 3 phase induction motor are split into two equal halves, a split phase induction motor results with two sets of stator coils with their axes separated by thirty electrical degrees. Such a machine can be operated from dual voltage source inverters (Fig. 1). The voltage ratings for the inverter devices are, in this case, nearly half the ratings for an equivalent three phase drive. If V_{DC} is the DC link voltage required for the three phase drive, a DC link voltage of $V_{DC}/(2 \cos 15^\circ)$ (rather than $V_{DC}/2$) is required for the split phase drive. This is because, when the windings are split, the resulting number of turns for the split winding is $N_s/(2 \cos 15^\circ)$ rather than $N_s/2$, where N_s is the equivalent number of turns of the three phase machine [1].

Since the switching states of the two inverters

FIG.1a SPLIT PHASE IM DRIVE

[Fig. 1] are independent of each other a total of 49 different voltage space phasor locations result for the split phase drive (Fig. 2). The switching states of the inverter for each voltage space phasor location, are indicated in Fig. 3. The voltage space phasors from the individual inverters form a

FIG.1b PHASOR DIAGRAM - SPLIT PHASE MOTOR

hexagonal structure [Fig. 3], with a 30° phase difference between the groups. By combination of the hexagonal vertices of the individual inverters, the resultant voltage space phasor locations can be made to form the vertices of a twelve sided polygon [Fig. 3]. PWM patterns for the two inverters can be generated by making use of the various space phasor locations.

FIG. 2 INTERIOR SPACE PHASOR COMBINATIONS

One possible PWM technique is to operate each of the inverters independently with space phasor modulation [2]. Each inverter will then generate the vertices of the corresponding hexagon. The resultant space phasor of motor voltage is then obtained by vector addition of the space phasors generated by the individual inverters. If the same voltage reference is given to both the PWM generators, then the two individual voltage space phasors will be separated by 30 electrical degrees. However, if the reference for the lagging phase group (A'B'C' - Fig. 1) is delayed by 30 electrical degrees, the individual voltage space phasors will be in the same direction and will add directly. By this means, a maximum value of $0.89655 V_{DC}$ can be achieved for the resultant voltage space phasor. This corresponds to an equivalent three phase peak fundamental phase voltage of $0.5977 V_{DC}$, as compared to $0.577 V_{DC}$ for a conventional 3 phase drive [1,2]. Since each inverter is operated with conventional three phase space phasor based PWM, using the hexagonal vertices, the average pole voltage waveforms contain only the third harmonic in addition to the fundamental. In the absence of neutral, the third harmonic voltages do not result in any current flow [1,2].

An alternative PWM technique is possible for the split-phase machine based on the vertices of the 12-sided polygon [Fig. 3]. In this method PWM patterns for the two inverters are generated by switching between the vertices of each of the 12 sectors of the polygon as appropriate [1]. The maximum resultant voltage space phasor that can be generated by this method is $0.9659 V_{DC}$. This corresponds to an equivalent three phase peak fundamental phase voltage of $0.643 V_{DC}$ for the motor. The extra boost in voltage is obtained because of the introduction of the 5th, 7th, 17th, 19th, etc. harmonic components in the average pole voltage waveform [1]. The stator mmfs due to these components cancel out in the air gap, because of the winding disposition, and therefore will not contribute to torque ripple. However, the corresponding components are present in the stator currents and their amplitude is only limited by the stator impedances. Therefore if the

FIG. 3 VOLTAGE SPACE PHASOR LOCATIONS FOR SPLIT PHASE INDUCTION MOTOR DRIVE AND THREE PHASE DRIVE

PWM technique is used down to the low speed range, the current stress on the inverter devices at low frequencies may be objectionable.

In this paper a PWM strategy is proposed for the split phase drive, wherein the first technique described above (using the hexagonal vertices) is used in the low speed range and the technique based on the 12 sided polygon is used in the high speed range. By this means the advantage of higher motor voltage in the modulation range is retained while avoiding high currents at low frequencies.

Section 2 and 3 give the principle of PWM generation for the above mentioned technique. Section 4 describes the hardware details of the PWM pattern generation. This includes the circuit for smooth transition between the two techniques. Section 5 presents the simulation as well as experimental results. The simulation is based on space phasor equations of the machine, the details of which are given in Section-6.

FIG. 4 SAMPLED REFERENCE VECTOR IN A SECTOR

intervals T_1 , T_2 and T_0 for each T_s interval (500 μ sec) with a resolution of 32 samples per sampling interval T_s . These are computed using eqn. (3) (for the 12 sided polygonal vertices) for 16 different α values (2^4) and 64 (2^6) different V_s values in a sector. It can be seen that the time duration for T_1 , T_2 and T_0 are the same for all 12 sectors for the same α and V_s . This requires an EPROM with 15 address lines or 32K memory. In EPROM-1, the duration for $T_0/2$ (initial zero state), T_1 (for V_1 state), T_2 (for V_2 state) and $T_0/2$ (for final zero state) are stored as bit patterns 00, 01, 10 and 11 respectively for a particular α and V_s in a sector [1,3]. In EPROM-2 the switching patterns are stored according to each of 12 sectors for each of the above bit patterns. EPROM-2 is addressed by the output of EPROM-1 and the sector information from the counter. The output of EPROM-2 is used for the inverter gating signals.

Since the hexagonal structure is used for the lower frequency range (up to an output maximum circular voltage space phasor amplitude of $0.8965 V_{DC}$) only 5 bits are used for the reference vector V_s . For the hexagonal vertices the span of ' α ' in a sector is 60° . So 5 bits are used for the α span and 3 bits are used for the sector (6-sector). This ensures the equal division of α span for the hexagonal as well as the 12 sided polygonal space phasor structure. For the hexagonal structure the address of EPROM-3 (periods T_1 , T_2 and T_0 for the ABC phase group) for the α position is incremented by 30° by the phase shifter in Fig. 7. EPROM-4 stores the inverter switching pattern for the ABC phase group. In EPROM-5 the switching periods for the A'B'C' phase group are stored and EPROM-6 gives the switching pattern for the A'B'C' phase group. The switching intervals T_1 , T_2 and T_0 for the hexagonal vertices are stored as in the case of 12 sided polygonal structure using the eqn. (1). From Fig. 7, it can be seen that the same speed reference signal addresses the EPROMs for the 12 sided polygonal voltage-space phasor operation as well as the hexagonal structure. The switching pattern for the hexagonal structure is used up to a certain frequency range, i.e., upto 40 Hz, above which (up to 50 Hz) the 12 sided polygonal structure is used. This is decided by the final selector block of Fig. 7. When the speed exceeds a threshold level (example 40 Hz) the selector immediately notices this using a comparator and it waits for the next immediate zero states for all the inverters to switch over to the 12 sided polygonal structure.

5. EXPERIMENTAL VERIFICATION

An experimental model of the proposed scheme is tested with a 2.5 KW split-phase motor. Fig. 8a shows the motor phase currents of the split-phase group A and A'. The sinusoidal nature of the current is because the hexagonal structure is used for the voltage space phasor PWM generation. The computer simulation of the same is shown in Fig. 8b in TUTSIM [2]. The theoretical model developed for the motor is explained in a later section. The experimental setup is driven using the 12 sided polygonal vectors for the voltage space phasor PWM generation. Fig. 9a shows the motor phase current and its harmonic spectrum under no load operation. Fig. 9a shows the presence of 5th and 7th harmonic currents in the motor phase. As these currents will not contribute to the air-gap flux, the impedance seen by these harmonic currents are due to the stator impedance only. Hence the larger amplitudes for these harmonics at lower speeds. The computer simulation of this is shown in Fig. 9b.

FIG.7 PWM PATTERN GENERATION

FIG.8a PHASE-A AND A' CURRENTS - EXPERIMENTAL RESULT (PWM USING HEXAGONAL VERTICES)

The motor configuration is simulated for the hexagonal structure as well as 12 sided polygonal structure and the transition between these two stages under no load operation is shown in Fig. 10. The system is operated under no load with simple V/f control without any speed feedback. It can be noted that there is a slight oscillation in the speed. This can be corrected with a simple feedback loop. Fig. 11 shows the transition under full load. Thus with a simple speed feedback loop, the split phase motor under voltage space phasor PWM operation can be implemented for the full frequency range without any current and torque transients. Thus this scheme

FIG.8b PHASE-A AND A' CURRENTS AND VOLTAGES
(SIMULATED RESULTS - PWM USING HEXAGONAL
VERTICES)

offers much better performance regarding voltage range as compared to conventional 3-phase scheme, still being in pulse width modulation.

6. SPLIT PHASE MOTOR MODEL IN SPACE PHASOR COORDINATES

In this section an equivalent motor model for the split phase induction motor is derived. The voltages and currents for the split phase groups are derived in space phasor form. The voltage and current equations for each phase group is derived with respect to its own reference axis; the reference axes for each are phase shifted by 30° (Fig. 12). For the rotor equation the conventional three-phase axis is used.

Stator-1 (A'B'C'-phase group)

$$R_s \dot{i}_{S1} + L_{ss} (d/dt) \{i_{S1}\} + \{1-\sigma_{12}\} L_{ss} (d/dt) \{i_{S2} e^{-j30}\} + L_{se} (d/dt) \{i_R e^{-j15}\} = v_{s1} \quad (4)$$

Stator-2 (ABC-phase group)

$$R_s \dot{i}_{S2} + L_{ss} (d/dt) \{i_{S2}\} + \{1-\sigma_{12}\} L_{ss} (d/dt) \{i_{S1} e^{j30}\} + L_{SR} (d/dt) \{i_R e^{j15}\} = v_{s2} \quad (5)$$

Rotor - defined with respect to rotor axis

$$R_r \dot{i}_R + L_{RR} (d/dt) \{i_R\} + L_{SR} (d/dt) \{i_{S1} e^{j(15-\epsilon)}\} + L_{SR} (d/dt) \{i_{S2} e^{j(15+\epsilon)}\} = 0 \quad (6)$$

Eqn. (6) can be written in terms of the rotor current referred to the three-phase (Fig. 12) stationary axes as:

$$R_r \dot{i}_R e^{-j\epsilon} + L_{RR} (d/dt) \{i_R e^{-j\epsilon}\} + L_{SR} (d/dt) \{i_{S1} e^{j(15-\epsilon)}\} + L_{SR} (d/dt) \{i_{S2} e^{j(15+\epsilon)}\} = 0 \quad (7)$$

where

R_s - six-phase stator resistance per phase

L_{ss} - six-phase stator inductance per phase

R_r - rotor resistance per phase

L_{RR} - rotor self inductance per phase

L_{SR} - rotor to six-phase stator mutual inductance

$(1-\sigma_{12})L_{ss}$ is the mutual inductance coupling coefficient term between the six-phase stator group including the leakage coupling coefficient.

ϵ - Rotor axis position with respect to 3 phase axis.

$$\text{Torque eqn. is } m_d = \frac{(2/3)(p/2)}{L_{SR}} \text{im. part of } \{i_{S1} e^{j15} + i_{S2} e^{-j15}\} i_R \quad (8)$$

These equations are used for the simulations presented in the paper. From the above equations the steady state equivalent circuit can be obtained and is shown in Fig. 13.

FIG.9a PHASE-A CURRENT SPECTRUM - PWM USING
12-SIDED POLYGONAL VERTICES

FIG.9b PHASE-A CURRENT - SIMULATED USING
12 SIDED POLYGONAL VERTICES

FIG.10 TRANSITION FROM HEXAGONAL VERTICES
TO 12 SIDED POLYGONAL VERTICES AT 40HZ
(UNDER NO LOAD OPERATION)

FIG.11 TRANSITION UNDER FULL LOAD
(TRANSITION FROM HEXAGONAL STRUCTURE TO
12 SIDED POLYGONAL STRUCTURE AT 40Hz)

FIG.12 SPACE PHASOR REFERENCE AXIS

7. CONCLUSION

An efficient voltage space phasor based PWM strategy for the split phase motor is developed. This scheme offers a wide speed range within the modulation range, more than that of a conventional scheme. The necessary PWM scheme developed is explained. An appropriate model for the split phase motor is developed and used in the computer simulation.

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FIG.13 SPACE PHASOR BASED EQUIVALENT CIRCUIT FOR SPLIT PHASE MOTOR