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Voltage modulation technique for a five-phase VSI supplying five-phase series connected two-motor drive

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ABSTRACT

This paper deals with series connection of stator windings and with decoupled dynamic control, it has been introduced recently. The two-motor drive system is supplied from a single five-phase voltage source inverter (VSI) and the machines are controlled using vector control scheme. In literature this drive configuration utilizes current control in the stationary reference frame so current fed machine models are employed and the current regulated PWM multi-phase inverter replicates the current references. If current control is to be implemented in the rotating reference frame, a PWM method for the five-phase VSI is needed to generate required reference voltages. This paper proposes voltage modulation scheme to generate five-phase inverter output signals using a simple approach, in such a way that independent and decoupled control of two five-phase series-connected machines is achieved with minimum interaction between the two machines. The proposed method offers significant advantages over the existing space vector PWM. The suggested method generates output voltages that contain two fundamentals at operating frequencies required by the two machines with reduced computational burden on digital signal processor (DSP). The concept is verified by simulation and experimental approach.

Introduction

Adjustable speed multi-phase (more than three phases) system proposed way back in 1969 [1] where five-phase induction motor drive supplied from a five-phase VSI operating in ten-step mode was analysed. However, great attention is being paid on the development of feasible multi-phase drive system in last decade [2]. A number of advantages of multi-phase drives are identified and reported in the literature such as reduced torque pulsation, high power density, quitter operation, lower per-phase converter rating etc.[3-10]. The detailed review on the state of art in the multi-phase motor drive systems is reported in [6,7]. The detailed reviews on the research on the specific configuration of dual three-phase machine are reported in [8] and the research on general multi-phase induction machines is presented in [9]. More recently the developments in the research on multi-phase drive systems are comprehensively presented by E. Levi in [2].

The high performance control of the PWM inverter fed ac motor drive is a challenging task and a great amount of work have been reported in the literature [11,12]. Among large number of PWM methods developed in the literature, carrier-based and space vector PWM methods became the most popular. Recently a generalized space vector PWM algorithm is reported for multi-level three-phase inverter including operation in overmodulation region [13] and for two-level three-phase inverter in [14]. Although these two PWM methods seem different but they have explicit relationship as described in [15] for two-level inverter and for multi-level inverter as it is elaborated in [16-17] and for five-phase VSI as it is reported in [18]. Generalized space vector PWM for multi-phase inverter based on duty ratio approach is reported in [19]. Experimental results pertaining to 5-phase and 7-phase inverters are presented in [19] to validate the findings. Analytical approach is used to establish the current ripple in multi-phase drives using space vector method in [20].

A novel concept for multi-motor drive systems, based on utilization of multi-phase machines and multi-phase inverters, have been proposed in [21-25]. Since vector control of any multi-phase machine requires only two stator current components, the additional stator current components are used to control other machines. It has been shown that, by connecting multi-phase stator windings in series with an appropriate phase transposition, it is possible to control independently all the machines with supply coming from a single multi-phase inverter. One specific drive system, covered by this general concept, is the five-phase series-connected two-motor drive, consisting of two five-phase machines and supplied from a single five-phase voltage source inverter. Such topology has been analysed in a considerable depth in [23-24] and experimental verification of the existence of control decoupling in this two-motor drive has been provided in [25]. The studies of [21-25] are based on inverter current control in the stationary reference frame, using phase current control in conjunction with hysteresis or ramp-comparison current controllers. The experimental rig of [25] utilizes ramp-comparison current control. A number of space vector PWM techniques have been reported for a five-phase VSI for single motor drive [18, 25-31] where attempts have been made to generate sinusoidal waveforms. Considering a five-phase system there exist two orthogonal planes namely *d-q* and *x-y*. Unwanted low-order harmonics are generated in the output of a five-phase VSI when the space vectors of *x-y* plane are not eliminated completely. This results in distortion in stator current and losses in the machine having sinusoidal mmf distribution. In case of

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concentrated winding machine, low order harmonic currents are injected along with the fundamental to enhance the torque production. In such cases it is desirable to produce low-order harmonic along with the fundamental as illustrated in [33- 35]. Research on multi-level multi-phase inverter is also gaining popularity as evident from recent publications on the development of space vector PWM for three-level five-phase VSI for single motor drive system [36-39] and five-phase series connected two-motor drive [40].

The applicability of current control in the rotating reference frame, using synchronous current controllers, has been investigated in [41] for series-connected five-phase two-motor drive system. It was shown that the same quality of control is achievable, provided that appropriately modified decoupling circuits are used in the *d-q* axis reference voltage generation. The simulation results provided in [41] are based on an ideal voltage source. However, any actual implementation of the current control in the rotating reference frame requires an appropriate PWM method in order to impose generated voltage references from vector controller. Although ramp-comparison method can be used for this purpose, the trend in digital control of ac drives has been for a long time to use space vector PWM. A space vector PWM scheme that would be applicable in conjunction with the series-connected five-phase two-motor drive system when current control is exercised in the rotating reference frame is proposed in [42] where two low-frequency components are produced. The major drawbacks of the proposed method in [42] is the lower dc bus utilization and occurrence of side band switching harmonics at multiple of half of the switching frequency of the inverter. These short comings were eliminated in [43] with the appropriate choice of space vectors. However, the method described in [42,43] typically uses sector identification and the calculation of the application times of space vectors is done on-line. This imposes a significant computational overhead on the DSP and makes this method quite complex. A modulation technique termed as “unified voltage modulation” scheme is proposed in [44] for a three-phase voltage source inverter. This method is based on the calculation of gating time of each inverter leg from the information of sampled reference voltages. This is the most general form of PWM encompassing carrier-based, carrier-based with harmonic injection, and space vector PWM. By simply modifying the shape of offset signal any of these modulation schemes may be realized. A similar voltage modulation approach is investigated in this paper for a five-phase VSI supplying two series-connected five-phase machines. It is important to note that the proposed modulation scheme does not depend upon the type of machines being fed by the modulated five-phase inverter. It is applicable to all types of machines (i.e. PMSM or Syn-Rel etc), and is valid for both series and parallel connected five-phase machine drives [45]. In the discussed voltage modulation scheme the gating time of ten inverter switches are obtained directly from sampled reference voltages; modulating the inverter for generating appropriate voltages for independently controlling the series-connected five-phase machines. This method offers the ease and simplicity of real time implementation without much burdening DSP with optimum dc bus utilization and without any change in the existing hardware. Complete algorithm is provided with their validation using simulation and experimentation.

Five-phase series-connected two-motor drive system

Five-phase series-connected two-motor drive supplied from a single five-phase inverter is discussed in the literature as a degree of freedom which is available in a five-phase system contrary to a three-phase system where no such additional freedom exists [19-25, 40]. The major advantage of this topology is the reduction in one inverter leg and one DSP when compared to two three-phase machines supplied from two three-phase inverters Although, such drive topology is seen as less attractive for general purpose applications but find excellent role in winder drives. The extra set of current components (*x-y*) available in a five-phase system could be effectively utilised for independently controlling an additional five-phase machine when the stator windings of two five-phase machines are connected in series and are supplied from a single five-phase VSI. Reference currents generated by two independent vector controllers, are summed up as per the transposition rules and are supplied to the series-connected five-phase machines. The experimental verification of the concept is detailed in [46]. Block diagram of the two-motor drive systems is illustrated in Fig. 1.

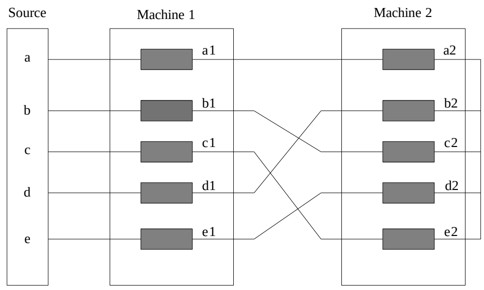


Fig.1 Five-phase series-connected two-motor drive structure

The schemes of series-connected five-phase two-motor drive discussed so far in the literature [21-25] utilize current control in stationary reference frame. However, if current control in the rotating reference frame is to be utilized, appropriate PWM scheme for five-phase VSI needs to be developed to generate voltage references instead of current references. The principle of decouple control of two five-phase series-connected machines lies in the fact that the *d-q* voltage/current components of one machine becomes the *x-y* voltage/current components of the other machine and vice-versa [21-25]. Since Space vector PWM offers higher dc bus utilization, the available literature focuses on the development of appropriate space vector PWM for two-motor drive system. In contrast this paper present simpler approach of generating gate pulses directly from the sampled reference voltage magnitude and thus offering great simplification in real time implementation.

2. Proposed voltage modulation scheme

Since in the two-motor drive of Fig. 1 inverter *d-q* plane is used to control the first machine while the inverter *x-y* plane is used to control the second machine, it is essential that the method of PWM generates only the required two fundamentals for the two machines, one in *d-q* plane and the other in the *x-y* plane. It is well known that the actual power flow between the inverter and motor takes place during the time interval called “effective time” when the voltage difference between the two inverter legs are non zero. The “effective time” can be relocated anywhere within the switching interval. The gating time of the inverter leg is derived by “effective time” relocation algorithm similar to the one used in [44]. The proposed modulation scheme utilises simply the sampled reference voltages to generate the gating time for which each inverter leg to yield two frequency output. The major advantage offered by the proposed scheme is its flexible nature. This is because relocation of “effective time” within the switching period results in various types of PWM scheme such as carrier-based, SVPWM, and discontinuous modulation.

Additionally, the computation time is greatly reduced as the sector identification and reference of lookup table is not used in the proposed algorithm contrary to the SVPWM techniques elaborated in [42,43]. In the proposed algorithm the reference voltages are sampled at fixed time interval equal to the switching time of the inverter leg.

The sampled reference voltage amplitudes are converted to equivalent time signals. The time signals thus obtained are imaginary quantities as they will be negative for negative reference voltage amplitudes.

Thus a time offset is added to these signals to obtain the gating time of each inverter leg in real sense. This offset addition centres the active switching vectors within the switching interval offering high performance PWM similar to SVPWM. The algorithm of the proposed scheme is given below, Where *Vx; x=a,b,c,d,e,f;* is the sampled amplitudes of reference phase voltages during sampling interval and T_s is the inverter switching period. *Tx; x=a,b,c,d,e,f;* are referred as time equivalents of the sampled amplitudes of reference phase voltages. T_{max} and T_{min} are the maximum and minimum values of *Tx* during sampling interval. T_o is the time duration for which the zero vectors is applied in the switching interval. T_{offset} is the offset time when added to time equivalent becomes gating time signal or the inverter leg switching time T_{gx}; *x=a,b,c,d,e,f* .

Algorithm of the proposed TESVPWM:

Sample the reference voltages V_a , V_b, V_c, V_d, & V_e in every switching period T_s.

Determine the equivalent times T_1,T_2, T_3,T_4, & T_5 given by expression, where *x a,b,c,d, and e ;*

$$T_{xs} = V_{xs} \times \frac{T_s}{V_{dc}};$$

Determine T_{offset}; $T_{offset} = \frac{T_S}{2} - \frac{T_{max} + T_{min}}{V_{dc}}$

Then the inverter leg switching times are obtained as

$$T_{gx} = T_x + T_{offset}; \quad x = a,b,c,d, \text{ and } e.$$

As an illustration a frequency combination of $f_1 = 2f_2$ is assumed where suffix 1 refers to supply for motor 1 and suffix 2 represents supply to motor 2. Fig. 2 shows the principal of the proposed voltage modulation method for a five-phase two-motor drive system for this frequency combination (here f_1 = 50 Hz, f_2 = 25 Hz). If one fundamental (lowest frequency) cycle is divided into ten equal parts and sampling is done in the first part, then the equivalent mathematical analysis for first part is given below and on the basis of this analysis the equivalent switching waveform is shown in Fig. 3.

For first part (*d-q* and *x-y*):

$$T_{max} = T_a; \qquad T_{min} = T_e;$$

$$T_1 = T_a - T_d; \quad T_2 = T_d - T_b; \quad T_3 = T_b - T_c;$$

$$T_4 = T_c - T_e;$$

$$T_{effective} = T_{max} - T_{min} = T_a - T_e;$$

$$T_0 = T_s - T_{effective}; \qquad T_{offset} = \frac{T_0}{2} - T_{min} = \frac{T_0}{2} - T_e$$

$$T_{ga} = T_a + T_{offset} = T_a + \frac{T_0}{2} - T_{min} = T_a + \frac{T_0}{2} - T_e$$

$$= \frac{T_0}{2} + T_1 + T_2 + T_3 + T_4$$

$$T_{gb} = T_b + T_{offset} = T_b + \frac{T_0}{2} - T_e = \frac{T_0}{2}{}_1 + T_3 + T_4;$$

$$T_{gc} = T_c + T_{offset} = T_c + \frac{T_0}{2} - T_d = \frac{T_0}{2} + T_4;$$

$$T_{gd} = T_d + T_{offset} = T_d + \frac{T_0}{2} - T_e = \frac{T_0}{2} + T_2 + T_3 + T_4;$$

$$T_{ge} = T_e + T_{offset} = T_e + \frac{T_0}{2} - T_e = \frac{T_0}{2};$$

$$T_1 = T_{ga} - T_{gd}; \quad T_2 = T_{gd} - T_{gb};$$

$$T_3 = T_{gb} - T_{gc}; T_4 = T_{gc} - T_{ge}; \qquad \frac{T_0}{2} = T_{ge};$$

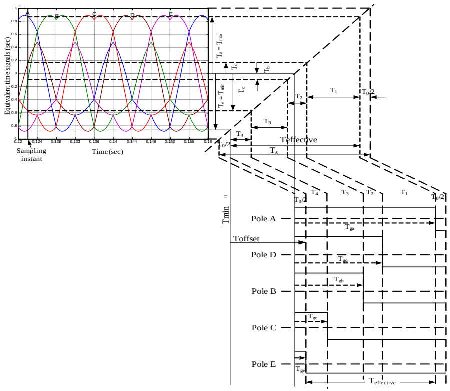


Fig.2 Principal of the proposed voltage modulation method

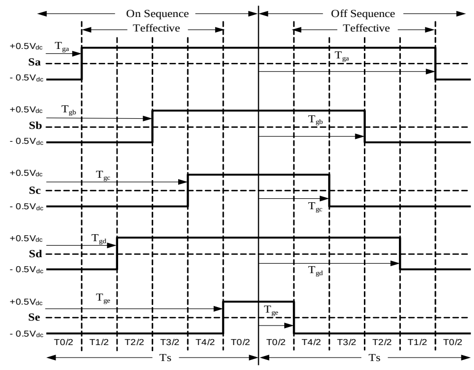


Fig. 3 Switching waveform for first part (*d-q* and *x-y*)

The switching pattern generated (Fig. 3) can be seen as having two symmetrical mirror images. The first part is denoted as ‘on sequence’ and the next part is called ‘off sequence’. The top trace illustrates the switching pattern for leg A, the next one in for leg B and so on with the bottom most representing the pattern of leg E. Considering now the leg A switching pattern, during ‘on sequence’, gate drive signal is given to the upper switch after a time interval of T_{ga} and it starts conducting and the lower switch is turned on in the ‘off sequence’ after a time interval of T_{ga}, however, a small dead time is introduced practically during turning on of the lower switch and turning off of the upper switch. The similar arguments hold good for other legs of the inverter.

Equivalence between presented voltage modulation scheme and svpwm

Equivalence between the proposed PWM approach and the existing space vector PWM method can be established as illustrated in this section. Once again considering Fig. 3 obtained from the proposed voltage modulation approach and the correspondence between the switching pattern and time of application of different vectors can be listed in Table 1. Here zeros represents lower power switches being ‘on’ and 1s represents upper switches being ‘on’.

As evident from Table 1, that generated switching state can be looked as the application of space vector number 11, 29, 22 and 14 and zero vectors for implementing SVPWM (Iqbal and Moinuddin, 2006). Although the proposed method does not directly act upon the space vectors, nevertheless it means here the implied vectors that are ultimately used to generate the required output voltage. These implied vectors are further shown in Fig. 4 in *d-q* and *x-y* planes.

Table 1: Vector mapping for Fig. 4

Time Interval	Switching state	Space Vector number
T_0	00000, 11111	0,31
T_1	10000	11
T_2	10010	29
T_3	11010	22
T_4	11110	14

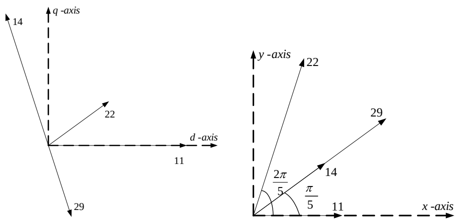


Fig.4 Vector representation in *d-q* and *x-y* plane for first part

Thus it is seen that only four space vectors are effectively applied to implement the modulation scheme. Thus the proposed method is similar to the one of SVPWM discussed in (Dujic *et al*, 2008) where only four active and one zero space vectors are used to realize the modulation scheme. Hence the advantages of using small number of space vector (only four) of scheme (Dujic *et al*, 2008) are also retained in the proposed method in addition to the simpler real time implementation. Division of parts in proposed unified voltage modulation approach can be viewed as equivalent sectors in SVPWM approach.

Simulation Results

The proposed method is simulated using Matlab/Simulink. The five-phase reference voltage is provided with amplitude equals to $\pm 0.5V_{DC}$ and V_{DC} is kept unity.

The switching frequency is chosen equal to 5 KHz. The maximum achievable output with the proposed method is equal to $0.325V_{dc}$ (same as SVPWM scheme of Dujic *et al*, 2008). Further the side band harmonic appears at the multiple of the switching frequency in contrast to the SVPWM scheme of (Iqbal and Levi, 2006) where it appears at half the switching frequency of inverter.

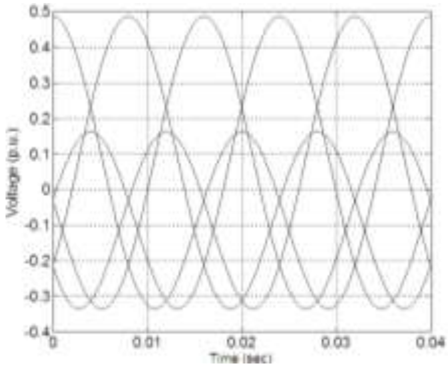
Simulation results are provided in Fig.5. The sampled reference phase voltages obtained are shown in Fig.5 (a) and then the equivalent time signals are calculated according to the proposed algorithm.

Then the actual gating time is obtained by adding offset to the equivalent time signals and the resulting waveforms for phase 'a', T_{ga} gating and T_{offset} are shown in Fig. 5 (b).

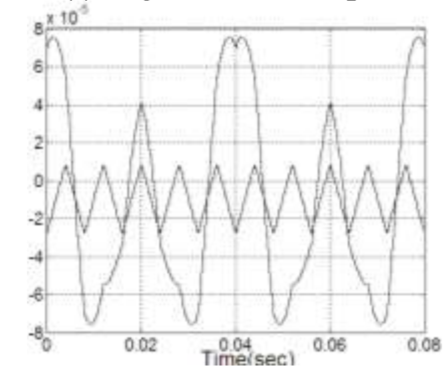
Fig. 5 (c) shows the equivalent gating signals (or modulating signals) for all the five phases and Fig. 5 (d) represents the offset time T_{offset}. The offset time is the middle portion of the $T_{offset.max}$ and $T_{offset.min}$, where $T_{offset.max} = T_s - T_{max}$, and $T_{offset.min} = -T_{min}$ [44]. The filtered output phase voltages are depicted in Fig. 5 (e).

The harmonic analysis of output voltage phase 'a' is carried out and the resulting time domain and frequency domain waveform is illustrated in Fig. 5 (f).

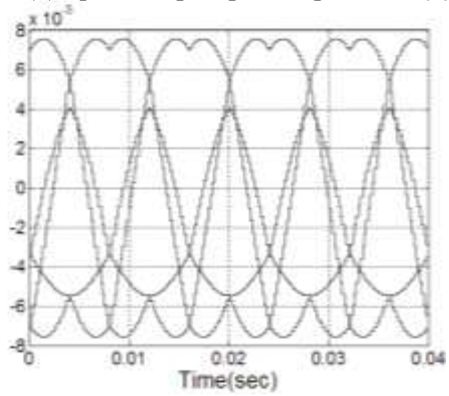
It is clearly seen from the spectrum that the inverter output phase voltage contain only two desired frequency components fulfilling the criteria of independent control of five-phase series-connected two-motor drive system.



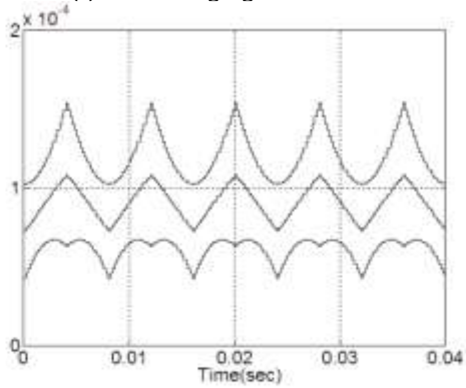
(a) Sampled reference voltages



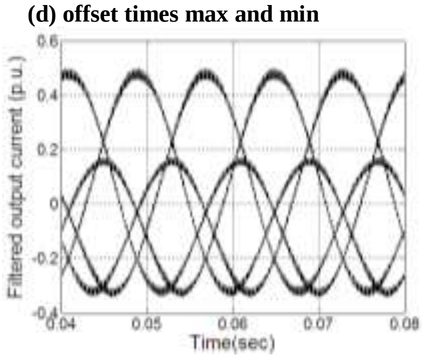
(b) equivalent gating time signals and t_{offset}



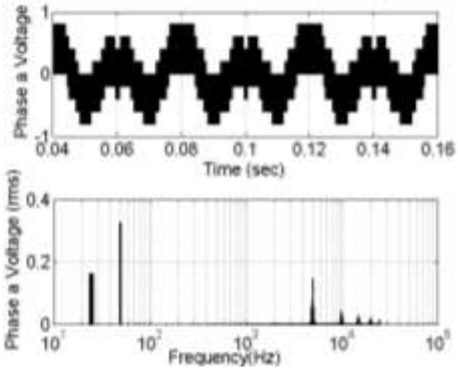
(c) modulating signals



(d) offset times max and min



(e) Filtered output phase voltages



(f) Harmonic spectrum of output voltage 'a'

Fig.5 Simulation results for inverter output for $f_2 = 2f_1$ combination.

Experimental Results

A five-phase voltage source inverter is developed using power module from VI Micro Systems, Chennai, India and the control signals are generated using Texas Instrument DSP TI320F2812. A RS232 cable is used to transfer the signals generated using PC to DSP board. The complete control code is written in C^{++} which is compiled using Code Composer Studio 3.3 and ASCI file is transferred to DSP using the printer port of the PC. The algorithm of SVPWM and the proposed voltage modulation are run in the DSP. The execution time in terms of clock cycles are noted for the two algorithms. The execution time is noted once the algorithm has been stored in the cache memory. It is found that the conventional SVPWM algorithm is executed in 182815 clock cycles while the proposed voltage modulation consumes 15356 clock cycles. Thus the implementation is much faster with the proposed method. Since the experimental results are identical with the SVPWM and the proposed method, only one set of results are shown which is obtained using the proposed scheme.

Two different sets of frequencies are chosen; one 25Hz & 50 Hz and 62.5 Hz & 125 Hz. The two fundamental frequencies sets are chosen with equal *v/f*.

These frequency component voltages are mixed as per the transposition rule shown in Fig. 1. A sample of switching signals for three legs is depicted in Fig. 8. The resulting filtered phase voltage and its FFT is depicted in Fig. 9 and Fig. 10 for 25 Hz & 50 Hz combinations and 62.5 Hz & 125 Hz combination, respectively.

The harmonic spectrum of phase 'a' voltage clearly shows only two fundamental frequency components with half the magnitude to satisfy constant *v/f* criteria. Thus the proposed PWM is capable of generating any frequency combination output for use in wide speed control of the two-motor drive system.

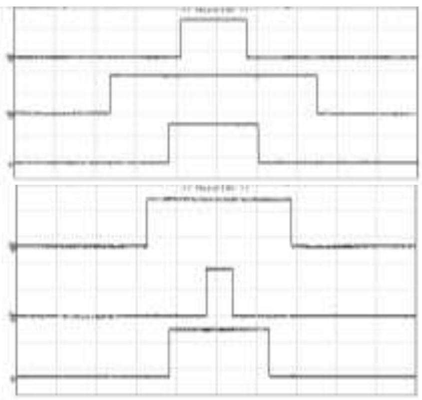


Fig. 8 Switching pattern for the proposed PWM

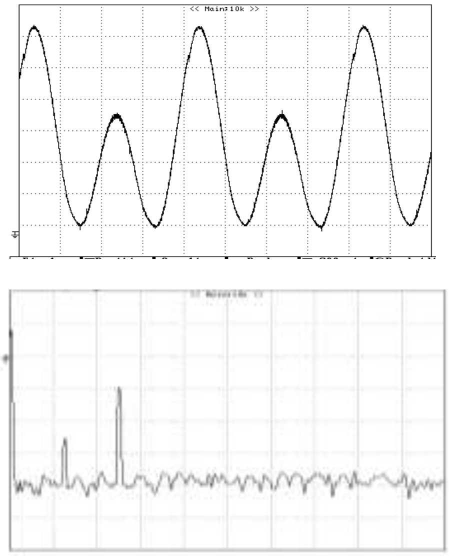


Fig. 9 Phase voltage and its spectrum for 25 Hz, and 50 Hz combination (50 V/div.)

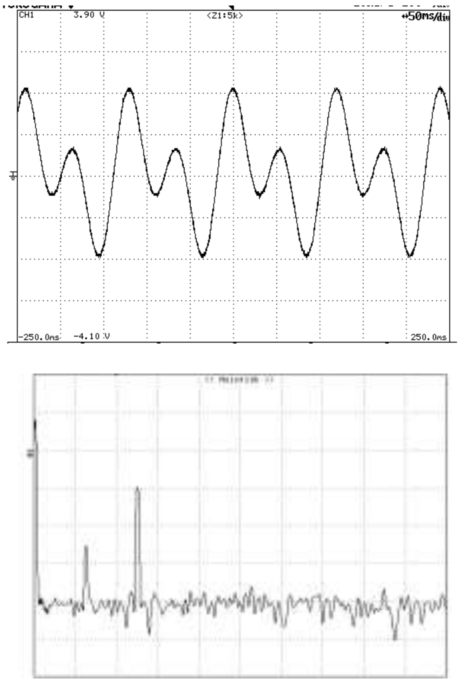


Fig. 10 Phase voltage and its harmonic spectrum for 62.5 Hz and 125 Hz combination (50 V/div.)

Conclusion

This paper presents a simple and effective voltage modulation scheme for a five-phase voltage source inverter. The single five-phase inverter is supplying two five-phase machines whose stator windings are connected in series and are independently controlled. In the proposed method, reference voltages are sampled at a regular interval to determine the inverter gating time. The proposed method offers a simple but effective approach to realise the two frequency output with the same quality as obtainable using complex SVPWM algorithm. The proposed technique offers major advantages in real time DSP implementation with low computational overhead. The Matlab/Simulink implementation and their simulation results are provided. The experimental verification of the approach is also presented.

References

1. E.E. Ward and H. H¨arer, Preliminary investigation of an inverter-fed 5-phase induction motor, *Proc. IEE* 116 (6), 1969, pp. 980–984.

2. E. Levi, "Multi-phase Machines for Variable speed applications" *IEEE Trans. Ind. Elect.*, vol. 55, no. 5, May 2008, pp. 1893-1909.

3. Apsley, J. M., Williamson, S., Smith, A. C., and Barnes, M., Induction motor performance as a function of phase number, *Proc. Inst.* Electr. Eng.—Electr. *Power Appl.*, vol. 153, Nov. 2006, no. 6, pp. 898–904.

4. Boglietti, R. Bojoi, A. Cavagnino and A. Tenconi, "Efficiency analysis of PWM inverter fed three-phase and dual three-phase induction machines," in *Conf. Rec. IEEE IAS Annu. Meeting*, Tampa, FL, 2006, pp. 434–440.

5. S. Williamson and A. C. Smith, "Pulsating torque and losses in multiphase induction machines," *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, Jul./Aug. 2003, pp. 986–993.

6. G.K.Singh; Multi-phase induction machine drive research – a survey, *Electric Power System Research,* vol. 61, 2002, pp. 139-147.

7. M.Jones, E.Levi; A literature survey of state-of-the-art in multiphase ac drives, *Proc. 37th Int. Universities Power Eng. Conf. UPEC,* Stafford, UK, 2002, pp. 505-510.

8. R. Bojoi, F. Farina, F. Profumo and Tenconi,"Dual three induction machine drives control-A survey", *IEEE Tran. On Ind. Appl.*,vol. 126, no. 4, pp. 420-429, 2006.

9. E. Levi, R.Bojoi, F. Profumo, H.A. Toliyat and S. Williamson, "Multi-phase induction motor drives-A technology status review", *IET Elect. Power Appl.* Vol. 1, no. 4, pp. 489-516, July 2007.

10. E.Levi, " Guest editorial", *IEEE Trans. Ind. Electronics*, vol.55, no. 5, May 2008, pp. –1891-1892.

11. J. Holtz, "Pulsewidth modulation-A survey" *IEEE Trans. On Ind. Elect.,* vol. 39, no. 5, pp. 410-420, Dec. 1992.

12. D.G. Holmes and T.A. Lipo, "*Pulse Width Modulation for Power Converters: Principle and Practice"* Piscataway, NJ: IEEE Press 2003.

13. A.K. Gupta and A.M. Khambadkone, "A general space vector PWM algorithm for multi level inverters, including operation in overmodulation range," *IEEE Trans. On Power Elect.* vol. 22, issue 2, March 2007, pp. 517-526.

14. Shu Zeliang, Tang Jian, G. Yulua and K. Jisan, "An efficient SVPWM algorithm with low computational overhead for three-phase inverters," *IEEE Trans. On Power Elect.* vol. 22, issue 5, Sept. 2007, pp. 1797-1805.

15. K. Zhou and D. Wang, "Relationship between space vector modulation and three-phase carrier based PWM – A comprehensive analysis", *IEEE Trans. On Ind. Elect.* vol. 49, no.1, Feb. 2002 , pp. 186-196.

16. C. Sourkounis and Ahmed Al-Daib, "A comprehensive analysis and comparison between multi-level space vector modulation and multi-level carrier-based PWM, *Proc. EPE-PEMC 2008,* Sept. 1-3 2008, pp. 1710-1715.

17. Y. Wenxi, H. Halbing and L. Zhengyu, "Comparison of space vector modulation and carrier-based modulation of multi-level inverter," *IEEE Trans. On Power Elect.* vol. 23, issue 1, Jan 2008, pp. 45-51.

18. Iqbal, SK. Moinuddin, "Comprehensive relationship between carrier-based PWM and space vector PWM in a five-phase VSI", *IEEE Trans. On Power Elect.* Vol. 24, no. 10, pp. 2379-2390, Oct. 2009.

19. D. Dujic, M. Jones, E.Levi, "Generalised space vector PWM for sinusoidal output voltage generation with multiphase voltage source inverter", *Int. Journal of Ind. Elect. And Drives,* vol. 1, no.1, pp.1-13, 2009.

20. D. Dujic, M. Jones, E. Levi, "Analysis of output current ripple rms in multi-phase drives using space vector approach", *IEEE Trans. On Power Elect.* Vol. 24, no. 8, pp. 1926-1938, Aug. 2009.

21. E. Levi, M. Jones, S.N. Vukosavic, "Even-phase multi-motor vector controlled drive with single inverter supply and series connection of stator windings," *IEE Proc. − Electric Power Applications,* vol. 150, no. 5, pp. 580-590, 2003.

22. E. Levi, M. Jones, S.N. Vukosavic, H.A.Toliyat, "A novel concept of a multi-phase, multi-motor vector controlled drive system supplied from a single voltage source inverter," *IEEE Trans. on Power Electronics*, vol. 19, no. 2, pp. 320-335, 2004.

23. E.Levi, M.Jones, S.N.Vukosavic, H.A.Toliyat, "A five-phase two-machine vector controlled induction motor drive supplied from a single inverter," *EPE Journal*, vol. 14, no. 3, pp. 38-48, 2004.

24. E. Levi, A. Iqbal, S.N. Vukosavic, H.A. Toliyat, "Modelling and control of a five-phase series-connected two-motor drive," *Proc. IEEE Ind. Elec. Society, Annual Meeting IECON,* Roanoke, Virginia, pp. 208-213, 2003.

25. Iqbal, S.N. Vukosavic, E. Levi, M. Jones, H.A. Toliyat, "Dynamics of a series-connected two-motor five-phase drive system with a single-inverter supply," *IEEE Ind. Appl. Society Annual Meeting IAS,* Hong Kong, 2005, pp. 1081-1088.

26. P.S.N. De Silva, J.E. Fletcher, B.W. Williams, "Development of space vector Modulation strategies for five-phase voltage source inverters," *Proc. IEE Power Electronics, Machines and Drives Conf. PEMD,* Edinburgh, UK, pp. 650-655, 2004.

27. Iqbal, E. Levi, "Space vector modulation schemes for a five-phase voltage source inverter, *11th European Conf. on Power Electronics and Applications EPE,* Dresden, Germany, 2005, CD-ROM paper 006.

28. Iqbal, E.Levi, "Space vector PWM techniques for sinusoidal output voltage generation with a five-phase voltage source inverter," *Electric Power Components and Systems,* vol. 34, no. 2, 2006, pp. 119-140.

29. Iqbal, "Analysis of space vector PWM for a five-phase voltage source inverter" *Journal of Institution of Engineers (IE),* India, vol. 89, Sept. 2008, pp. 8-16.

30. H.A. Toliyat, M.M. Rahimiam and T.A. Lipo, "Analysis and modeling of five-phase converters for adjustable speed drive applications," *Proc. EPE,* Brighton, UK, 1993, pp. 194-199.

31. H.A. Toliyat, R.Shi and H.Xu, "A DSP-based vector control of five-phase synchronous reluctance motor," *Conf. Rec. IEEE IAS Annual Meeting,* Rome, Italy, 2000, pp. 1759-1765.

32. D. Casadei, G. Serra, A. Tani and L. Zarri, "Multi-phase inverter modulation strategies based on duty cycle space vector approach," *Proc. Of Ship Propulsion and Railway Systems Conf. SPRTS,* Bologna, Italy, 2005, pp. 222-229.

33. R.O.C. Lyra, T.A. Lipo, "Torque density improvement in a six-phase induction motor with third harmonic current injection", *IEEE Trans. Ind. Appl.,* vol. 38, no. 5, pp. 1351-1360, Sept./Oct. 2002.

34. M.J. Duran, F. Salas, M.R. Arahal, "Bifurcation Analysis of five-phase induction motor drives with third harmonic injection", *IEEE Trans.* On Ind. Elect. vol. 55, no. 5, pp. 2006-2014, May 2008.

35. M.R. Arahal, M.J. Duran, "PI tuning of Five-phase drives with third harmonic injection", *Control Engg. Practice,* 17, pp. 787-797, Feb. 2009.

36. O. Lopez, J. Alvarze, J. Doval-Gandoy, F.D. Freijedo, "Multilevel multiphase space vector PWM algorithm", *IEEE Trans. On Ind. Elect.*, vol. 55, pp. 1933-1942, May 2008.

37. Lopez, J. Alvarze, J. Doval-Gandoy, F.D. Freijedo, "Multilevel multiphase space vector PWM algorithm with

switching state redundency", *IEEE Trans. On Ind. Elect.,* vol. 56, pp. 792-804, March 2009.
38. M. Hutson, G. K. Venayagamoorthy, K. A. Corzine, "Optimal SVM switching for a multilevel multiphase machine using modified discrete PSO," IEEE Swarm Intell. Symp., 21-23 September, USA, pp. 1-6, 2008.
39. Gao Liliang and John E. Fletcher, "A space vector switching strategy for 3-level 5-phase inverter drives", *IEEE Trans. On Ind. Elect. (on-line version available),* 2010.
40. N.R. Abjadi, J. Soltani, J. Askari, Gh. R. Arab Markadeh, "Three-level five-phase space vector PWm inverter for a two five-phase series connected induction machine drive", *Energy and Power Engineering,* pp. 10-17, 2010.
41. M. Jones, E. Levi, A. Iqbal, "Vector control of a five-phase series-connected two-motor drive using synchronous current controllers," *Electric Power Comp. & Systems,* vol. 33, no. 4, pp. 411-430, 2005.
42. Iqbal, E. Levi, "Space vector PWM for a five-phase VSI supplying two five-phase series-connected machines", *12th Int. Power Electronics Motion Control Conf., EPE-PEMC 2006,*Portroz, Slovenia, Aug 30-Sep 1,2006 , CD-ROM paper.
43. Dujic, G. Grandi, M. Jones and E. Levi, "A space vector PWM scheme for multi-frequency output voltage generation with multi-frequency with multi-phase voltage source inverter", *IEEE Trans. Ind. Electronics,* vol. 55, no. 5, May 2008, pp. 1943-1955.
44. D.W.Chung, J.S. Kim and S.K. Kul, "Unified voltage modulation technique for real-time three-phase power conversion", *IEEE Trans. Ind. Application,* vol.34, no.2, March-April 1998, pp.374-380.
45. M. Jones, S. N. Vukosavic, E. Levi, "Parallel-connected multiphase multidrive systems with single inverter supply," *IEEE Transactions on Industrial Electronics,* Vol. 56, No. 6, pp. 2047–2057, June 2009.
46. Levi, M. Jones, S.N. Vukosavic, A. Iqbal, H.A. Toliyat, "Modelling control and experimental investigation of a five-phase series-connected two-motor drive with single inverter supply", *IEEE Trans. On Ind. Elect.,* vol. 54, no. 3, June 2007, pp/ 1504-1516.
47. Iqbal, S. Moinuddin, "Space vector model of a five-phase voltage source inverter", *IEEE Int. conf. on Industrial Technology (ICIT 06),* 15-17 Dec. Mumbai, India, CD_ROM paper no. IF002909, 2006, pp. 488-493.

Appendix 1: Motor Data

$R_s = 10\Omega; R_r = 6.3\Omega; L_s = 0.46H; L_r = 0.46\,H,$

$L_m = 0.42; P = 4; J = 0.03; B = 0.0001;$

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