01 Jul 2005

Multilevel Multi-Phase Propulsion Drives

Shuai Lu

Keith Corzine
Missouri University of Science and Technology

Recommended Citation

S. Lu and K. Corzine, "Multilevel Multi-Phase Propulsion Drives," *Proceedings of the IEEE Electric Ship Technologies Symposium, 2005*, Institute of Electrical and Electronics Engineers (IEEE), Jul 2005.
The definitive version is available at https://doi.org/10.1109/ESTS.2005.1524701

2005 IEEE Electric Ship Technologies Symposium

Multilevel Multi-Phase Propulsion Drives

Shuai Lu, *Student Member, IEEE*, and Keith Corzine, *Member, IEEE*

Department of Electrical Engineering, University of Missouri - Rolla
1870 Miner Circle, Rolla, MO 65401-0040

***Abstract*—This paper presents a comprehensive analysis of the 5-phase induction motor driven by voltage-source inverter drives and particularly its steady-state performance evaluation. The performance of various modulation methods are analyzed with insightful look into their harmonic content and torque ripple. Three separate methods are proposed to reduce the torque ripple for low, middle and high modulation index regions while eliminating or controlling the non-torque-producing harmonics within the current machine rating. A complete set of simulations are carried out to verify the concepts and proposed methods. The multi-level multiphase topology is introduced and it is compared to the two-level system. The modification of switching sequence for reduction of torque ripple is applied to the three-level 5-phase motor drive. Application of the multilevel multi-phase concept to high power motor drives (as well as motor design and selection) is discussed.**

I. BACKGROUND

The multiphase motor concept was introduced 35 years ago and witnessed a new surge of research interest in recent years due to the technological advancement of the power electronic switching devices and also because of the emerging development of the specialized applications such as electric vehicle, aircraft, locomotive traction and naval electric ship propulsion systems, which require high performance and reliability. The major advantages of the multiphase motor and drive system are high reliability, fault tolerance and higher power density.

A power converter with five phase legs provides more available voltage vectors compared to a three phase converter, so the output of the modulator can have higher resolution. Extensive research [1-5] has been carried out successfully using current/flux regulated control such as vector control, DTC, etc, in the five phase motor drive. Therein, the modulators implicitly select suitable voltage vectors with the hysteresis band of current or flux command.

Some analysis [6,7] was carried out in 5-phase voltage-source inverter (VSI) control, which is particularly interesting in 5-phase system where the abundance of the voltage vectors, the different vector patterns than three-phase system and its unique property of multiple *d-q* planes. These specific properties provide considerable potential for further exploration in terms of performance improvement. Compared with the 3-phase system, the 5-phase poses more complexity and the methodology and some well-known facts in 3-phase systems can't be adapted to the five phase system.

In the existing literature, much of the effort is focused on how to eliminate the phase current harmonics while there's no special consideration given to optimization of the torque ripple performance. Unlike the 3-phase system, a phase current in five-phase system devoid of harmonics *doesn't* necessarily indicate smoother torque output. On the contrary, it is shown in the paper that they are tradeoffs to each other. This abnormality is due to the existence of multiple d-q coordinate planes. By transforming the 5-phase variables into multiple reference frames, the torque producing harmonics (including the fundamental) are projected into the dq1 plane, and the remaining harmonics are projected into other d-q planes, where they deform the phase current and cause additional stator copper loss. The generic rule for harmonic free modulation methods and their limitations are introduced and analyzed in detail. Then the optimal torque ripple modulation and the harmonics it induces are discussed.

In this paper, the torque ripple performance and phase current harmonics under low, middle and high modulation index are addressed in detail. For each modulation index range, a separate modulation method is proposed to achieve optimized torque output while either eliminating harmonics (in low and middle modulation index region) or keeping the harmonics within the machine rating (in high modulation index region). For many applications including naval propulsion systems where torque ripple performance outweighs the consideration of extra copper loss from the non-torque-producing harmonics, the proposed methods should be especially preferable.

So far, all existing multiphase research is limited to two voltage levels per phase leg. In this paper, the initial attempt to integrate the multi-level and multiphase topology is made. It combines the advantages of both technologies and is shown to have even higher torque ripple performance than two-level drives. Then in the given three-level 5-phase example, the switching sequences (per DSP cycle) and its relation to the torque ripple reduction is introduced briefly. Further torque ripple reduction is observed with an improved switching state sequence.

Finally, the paper gives brief suggestions for the high power applications of the 5-phase VSI drive. The cascaded topology is recommended and simple considerations for motor selection are given to minimize harmonic current in proportion to the fundamental component.

II. MULTI- PHASE GENERIC ANALYSIS

In various multi-phase studies, *m*-dimensional machine variables need to be transformed into a new coordinate system. The transformation matrix used and the resulting coordinate systems varies considerably. However, there's some commonality among these methods [1,5,6]. The *m*-phase motor with *m*-dimensional variables must be decoupled into the dq1 plane which is aligned with the rotating flux plane, and three remaining degrees of freedom (*m*-2) can be decomposed into either multiple dq-x planes, multiple individual zero sequence variables or a combination of both. As long as the transformation makes all resulting axis orthogonal, their phase voltage and current by reverse transformation will be the same. For example, it can be verified that the two different 5-phase machine models [1] and [5] by different transformations return the same phase current after the reverse transformation.

The fundamental and the harmonic producing rotating MMF will be transformed into dq1 plane so the harmonics in dq1 plane causes pulsation of the torque. The other set of harmonics enters

0-7803-9259-0/05/$20.00 ©2005 IEEE.

"non-torque producing" planes or variables. They cause extra copper loss in the motor while not deforming the rotating MMF and torque output. It'll be further exemplified in the 5-phase motor example that these components have different equivalent circuits. Except for the variables in dq1 plane, the other variables have the equivalent circuit which includes winding resistance and leakage inductance in series. So the harmonics current could be very large with even a small amount of harmonic voltage input in coordinates other than dq1 plane.

III. FIVE-PHASE CONVERTER AND MOTOR MODELLING

For motor drive analysis with two-level 5-phase induction motor in Figure 1 (assuming sinusoidally distributed windings), it is preferred that the 5-dimensional inputs and machine variables be transformed into dq1 and dq2 reference frames with a zero sequence variable [1]. This decomposition is particularly convenient for the harmonic analysis. In the 5-phase system, the harmonic set with contribution to the rotating MMF (torque production) are $10n \pm 1$ (n=1, 2, 3...) and they are transformed into dq1 plane. The harmonic set having no contribution to torque production are $5n \pm 2$ (n=1, 2, 3...) and they go into the dq2 plane. This is different from the 3-phase system, where all the harmonics except for those with the order of multiple of three contribute to the torque production. In the three-phase system, a phase voltage or current with less harmonics usually indicates better motor performance.

For a 5-phase induction motor fed by two-level VSI converter, the line-to-ground voltage can be calculated using $v_{xg} = s_x \cdot v_{dc}$ where $x = a,b,c,d,e$ and s_x is the per-phase switching state having a range of $s_x = 0,1$. The line-to-neutral voltage can be expressed by

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ v_{ds} \\ v_{es} \end{bmatrix} = \frac{1}{5}\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}\begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \\ v_{dg} \\ v_{eg} \end{bmatrix} \qquad (1)$$

The line-to-neutral voltages can be transformed to the dq planes using the transformation matrix [1]

$$K = \begin{bmatrix} \cos\theta & \cos(\theta-\frac{2}{5}\pi) & \cos(\theta-\frac{4}{5}\pi) & \cos(\theta+\frac{4}{5}\pi) & \cos(\theta+\frac{2}{5}\pi) \\ \sin\theta & \sin(\theta-\frac{2}{5}\pi) & \sin(\theta-\frac{4}{5}\pi) & \sin(\theta+\frac{4}{5}\pi) & \sin(\theta+\frac{2}{5}\pi) \\ \cos\theta & \cos(\theta+\frac{4}{5}\pi) & \cos(\theta-\frac{2}{5}\pi) & \cos(\theta+\frac{2}{5}\pi) & \cos(\theta-\frac{4}{5}\pi) \\ \sin\theta & \sin(\theta+\frac{4}{5}\pi) & \sin(\theta-\frac{2}{5}\pi) & \sin(\theta+\frac{2}{5}\pi) & \sin(\theta-\frac{4}{5}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (2)$$

After the transformation, the machine variables and motor equations are decoupled into the dq1 and dq2 planes plus a zero sequence component. (The detailed process of 5-phase motor model transformation is given in [1]). Each plane has its own equivalent circuit. For dq1 plane, the equivalent circuit and its inverter voltage vector plot are shown in Figure 2. It is very

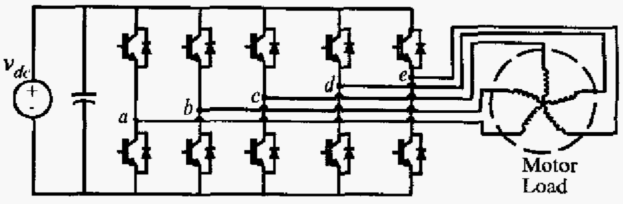


Figure 1. Typical five-phase 2-level motor drive.

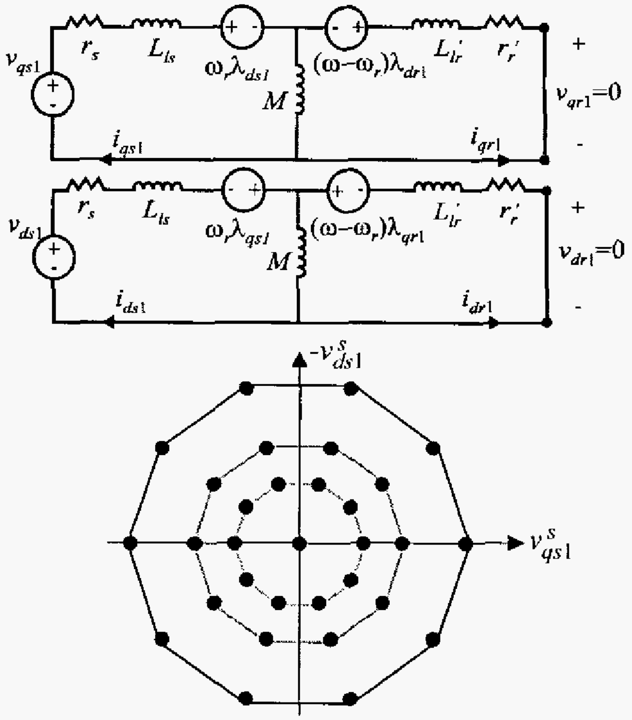


Figure 2. The dq1 plane equivalent circuit and vector plot.

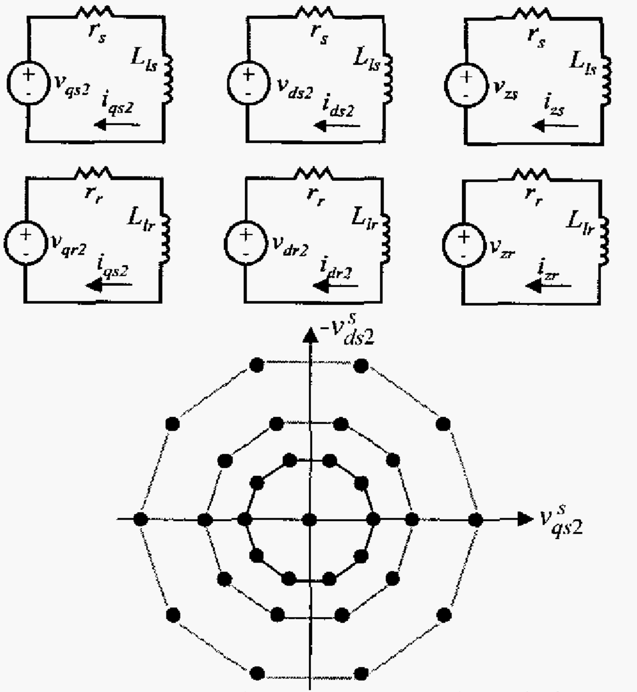


Figure 3. The dq2 plane and zero sequence equivalent circuit and dq2 plane vector plot.

similar to the d-q model of a 3-phase induction motor. The set of differential equations for simulation is formulated as follows:

$$\begin{bmatrix} p\lambda_{qs} \\ p\lambda_{qr} \\ p\lambda_{ds} \\ p\lambda_{dr} \end{bmatrix} = \begin{bmatrix} & & -\omega & 0 \\ & & 0 & -(\omega-\omega_r) \\ \omega & 0 & & \\ 0 & (\omega-\omega_r) & & \end{bmatrix} \begin{bmatrix} \lambda_{qs} \\ \lambda_{qr} \\ \lambda_{ds} \\ \lambda_{dr} \end{bmatrix} + \begin{bmatrix} -r_s & & & \\ & -r_r & & \\ & & -r_s & \\ & & & -r_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{qr} \\ i_{ds} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} v_{qs} \\ v_{qr} \\ v_{ds} \\ v_{dr} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_{qs} \\ i_{qr} \\ i_{ds} \\ i_{dr} \end{bmatrix} = \begin{bmatrix} l_{ls}+l_m & l_m & & \\ l_m & l_{lr}+l_m & & \\ & & l_{ls}+l_m & l_m \\ & & l_m & l_{lr}+l_m \end{bmatrix}^{-1} \begin{bmatrix} \lambda_{qs} \\ \lambda_{qr} \\ \lambda_{ds} \\ \lambda_{dr} \end{bmatrix} \tag{4}$$

$$T_e = \frac{5}{2}\frac{P}{2}(\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}) \tag{5}$$

The equivalent circuits for the dq2 plane and zero sequence variables are shown in 3. It only has the winding resistance and leakage inductance. For the non-torque-producing harmonics voltage, the circuit has low impedance and no back EMF to limit the induced current. Therefore, for VSI operation, even if a small harmonic voltage is coupled into the dq2 plane, considerable harmonic current will be induced. The phase current is obtained by the reverse transformation. It is the sum of the q-axis currents of dq1, dq2 planes and zero sequence.

$$i_{as} = i_{q1s} + i_{q2s} + i_{zs} \tag{6}$$

Note that i_{zs} will always be zero for star-connected 5-phase stator winding.

The 5-phase inverter has total $2^5 = 32$ available switching states. These 32 vectors form a decagon pattern in each plane after the transformation. Before the harmonics analysis, it is important to emphasize one important relation between these two decagons. For the 32 vectors in both planes, they can be divided into 4 groups which consist of three decagon rings (outer, mid and inner) and 2 vectors at the origin as indicated in figure 2 and 3 with different darkness. All the vectors at the outer ring in dq1 plane belong to the inner ring in dq2 plane and all vectors at the inner rings in dq1 plane go to the outer ring in the dq2 plane.

IV. FIVE-PHASE SYSTEM HARMONIC STUDY

The easiest way to avoid harmonics in phase voltage/current is to create PWM with explicit sinusoidal voltage/current command per-phase. In VSI control, natural sample modulation is the most straightforward way to do this.

It is instructive to see the vector traversal sequence of the natural sampling process in Figure 4. There are five level transitions per DSP cycle (one per phase), and totally six switching states (vectors) is to be traversed per cycle. For example, when the reference is located in the [0°, 36°] sector, the switching sequence always follows the order (00000-10000-11000-11001-11101-11111) back and forth. It can also be proven analytically that the vector in the outer ring (11000) will always have the dwell time 1.618 times that of their corresponding mid ring vector (11101). This timing constraint guarantees the sum of the six vectors in dq2 plane to be zero. To illustrate this, the zero vectors at origin and the four vectors (10000, 11001, 11000 and 11101) in the outer trapezoid in dq1 plane are as labeled with larger gray dots in dq2 plane. According to the geometrical relations, the ratio between the vector lengths (11101 vs. 11000 and 10000 vs. 11001) is 1.618:1. Therefore these four vectors in dq2 plane completely cancel each other in one DSP cycle and there are no low order harmonics in v_{q2s} and i_{q2s} to be added into the phase voltage/current, and v_{as} and i_{as} appear sinusoidal as shown in Figure 4.

However, the (1.618:1) timing constraint will limit the natural sample operation range (modulation index) within m=1.05 which is much lower than the inscribing circle of the decagon at m=1.23 ($0.615v_{dc}$), where the maximum dc link utilization is obtained. It can be proven by geometrical computation that to have modulation index higher than 1.05 ($0.525v_{dc}$), the time ratios between the two outer ring vectors and mid-ring vectors should be larger than 1.618:1 (the zero vector dwelling time is zero already). And at the maximal boundary (edge of decagon), the two outer ring vectors together will have a 100% duty ratio (the time ratio becomes infinity).

Also note that in natural sampling, fifth harmonics can be added into the sinusoidal reference per-phase to boost the output magnitude by 5% (from m=1.0 to m=1.05). Unlike the 3-phase system, where the per-phase 3rd harmonics injection can boost the operating range to the edge of the hexagon, the 5-phase system maximal modulation boundary is m=1.23 (0.615Vdc) and it is much higher than what the natural sample method can reach.

From the natural sample case, it can be further concluded that in a 5-phase system, it takes at least two pairs of vectors besides the zero vector to cancel each other in dq2 plane. There are multiple options to select these vectors. Natural sampling generates such two pairs implicitly (within a trapezoid). Another way of vector selection was introduced in [6], where the four neighboring vectors spanning along the outer ring was used. Note

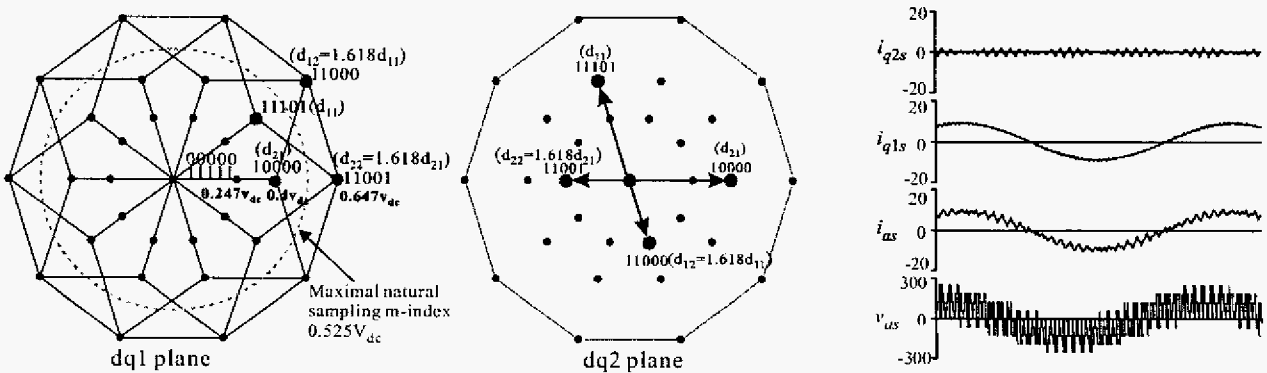


Figure 4. Natural sample modulation switching sequence and timing with cancellation in dq2 plane.

that it was used in the 6-phases system, but it turns out to be applicable in 5-phase case as well. This method is illustrated in Figure 5. With it, the maximal modulation index also can not reach the maximal limit (m=1.23), due to the constraint of the timing ratio between the two pairs of the vectors.

Consider what happens if only one pair of vectors plus the zero vector are used to produce the reference with a circular locus in the dq1 plane. In Figure 6, the corresponding space vector locus (fast average) is plotted in the dq2 plane. The locus shape indicates the combination of 3rd and 7th harmonics in the dq2 plane. They will superpose onto the fundamental component in dq1 plane and the phase voltage/current (v_{as} and i_{as}) will thus be deformed. Since the fundamental voltage and 3rd and 7th harmonic voltages apply onto different equivalent circuits, the harmonic current will have a different phase shift. The fundamental will lag by $\cos^{-1}(0.8)$ (assuming power factor = 0.8) and 3rd and 7th harmonics will lag by almost 90° (assuming stator resistance is negligible). Also the small impedance in dq2 plane induces large magnitude harmonic current which is almost comparable to that of the fundamental. The simulation results shown in figure 6 match the above theoretic predictions well.

V. TORQUE RIPPLE STUDY

When a power converter is used for motor drive applications, its steady state output performance is usually evaluated in terms of torque ripple (in percent). In a three-phase system, the phase voltage and current THD is directly related to the torque ripple, so they serve as the best indicator for the output performance. All kinds of proposed schemes in this area have their ultimate goal of reducing the current THD and obtaining smoother torque output.

Summarizing the previous work in power converter/motor drive innovations, there are two distinct research directions for THD/torque ripple reduction (Given a fixed PWM frequency):

1. The higher modulation resolution (smaller size of the area formed by encompassing vectors of the reference vector). This is exemplified by myriads of multi-level topologies proposed over the last decade.
2. The optimal switching sequence which makes the smoother discrete steps within each DSP cycle when approximating the reference.

However, in the 5-phase system or other multi-phase system, the phase current THD is no longer a relevant indicator for torque output performance. Only the dq1 plane voltage vectors are related to the torque production and the abundance of vectors (3 layers of vectors along the decagon rings) makes it possible to have higher modulation resolution. This is illustrated in Figure 7. This paper will be first on how to exploit the potential of the vectors abundance of the multiphase converter to minimize the torque ripple. The switching sequence and its relation to further torque ripple reduction will be discussed in a later section.

In a 5-phase system, for the smallest possible torque ripple, the nearest voltage vectors in dq1 plane must be used in space vector modulation (SVM). As in figure 7, this is similar to the case in 3-phase system where multi-level offers closer set of 3 vectors enclosing the reference. With the multiplicity of the phase number, even two levels provide multi-layers of available vectors and much closer sets of vectors.

This process, however, will not guarantee the cancellation of the vectors in dq2 plane and could induce large harmonic current in the low impedance dq2 plane circuit. So this "nearest vector SVM modulation" has to be used with caution. As will be discussed in next section, the harmonic magnitude and phase angle changes over m index, and this maximal torque ripple reduction scheme can't be used over the whole m index range.

The natural sample modulation is a good option for the total elimination of the low order harmonics over the full range of the m-index; however, its torque ripple performance is not optimal since it's not using closest set of vectors. Particularly when modulation index is low, its torque ripple percentage increases dramatically. It can be shown that the natural sampling process always uses the four vectors on the outer trapezoid plus the zero vector for any reference magnitude. The smaller m-index gets, the longer the zero vector dwelling time, which implies larger torque ripple. This problem is demonstrated in Figure 8. It compares the torque ripple when m=0.55 and m=0.9. For comparison purposes, the DC voltages are adjusted to give same average torque output.

Summarizing the discussion above, the following conclusion can be made: In a 5-phase system, torque ripple and phase

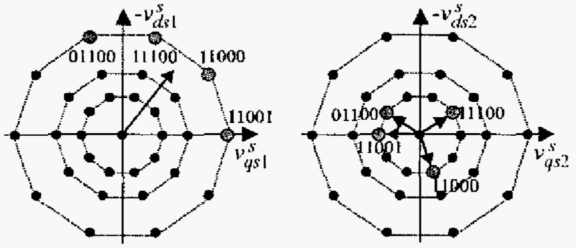


Figure 5. Modulation using two pairs (4 neighboring vectors) spanning in outer ring to have harmonic free operation.

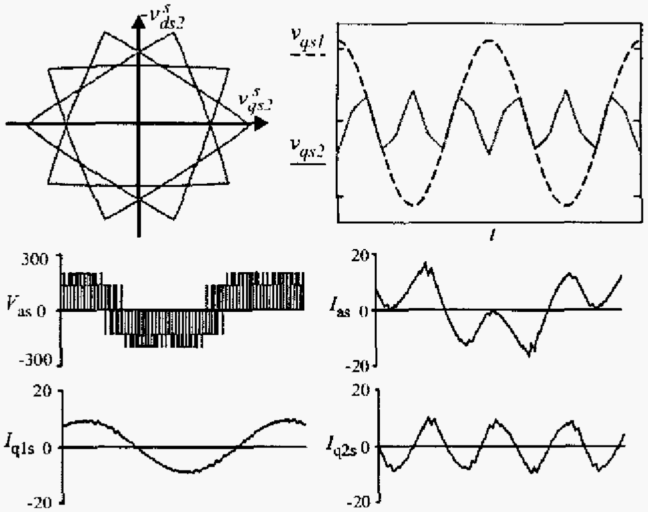


Figure 6. Modulation with a single pair of vector sand its dq2 plane voltage and current harmonics.

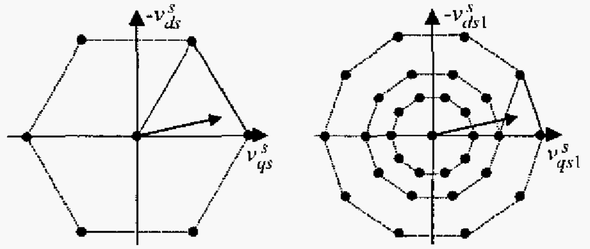


Figure 7. 3-phase 2-level SVM PWM vs. 5-phase 2-level SVM PWM

harmonics current are tradeoffs. In cases of natural sample VSI or current/flux regulated control where sinusoidal current is either commanded or present as a result, the torque performance is not optimal. The corollary is that as long as the current waveform appears sinusoidal, the dc link voltage can't be fully used.

VI. PROPOSED MODULATION METHODS FOR OPTIMAL TORQUE RIPPLE PERFORMANCE

As discussed previously, the SVM using closest vectors in dq1 plane results in smoother torque output. However, the harmonics induced into the phase current (mostly non-torque producing harmonics) need to be controlled within the machine rating, even when the consideration of extra copper loss is outweighed by the torque performance in many applications.

Using the nearest vectors principle in modulation, both the magnitude and phase angle of harmonic current changes over the different values of modulation index so it is necessary to divide the operation range into three parts (low, mid, and high regions as indicated in Figure 9 by regions 1, 2, 3).

First, in low modulation index, the top priority is to cancel out the low order harmonics while, if possible, using vectors as close as possible. This is because when the reference vector magnitude is small, the vectors closest to it (inner rings in dq1 plane) go to the outer ring in the dq2 plane as seen in Figures 2 and 3. These vectors with larger magnitude in dq2 plane, if not cancelled out, will induce large harmonic current well beyond machine rating.

The natural sampling process, as shown previously, produces much larger torque ripple (in percent) in the low modulation index region. This is because it uses the two pairs of vectors on the outer trapezoid which are not close to the reference. Actually, for the low modulation index (region 1), there exist a much closer pair of vectors which can also cancel each other in dq2 plane given a certain duty ratio. For example, the new set of four vectors are (01001, 10000, 11101 and 11010) which forms inner trapezoid in figure 10. In the dq2 plane, the vector 11101 cancels vector 11010 in the opposite direction if the timing ratio between them is set to 1.618: 1 and the same rule hold for vector 10000 and 01001. The switching sequence and timing ratios for the new set of vectors can be handily generated by the natural sample modulator, the only modification to do is to "normalize" the reference vector (multiplying its magnitude by 1.618) and use natural sample modulator to get the sequence and timing, then replace the resultant switching states (forming the outer trapezoid) with those from the inner trapezoid. A small lookup table is needed here and only four entries for mapping (for sector 1 [0°, 36°]) is need in the table. Since closer vectors are used, much smaller torque ripple is achieved by this method compared with natural sample modulation. Also the volts/sec fast average per DSP cycle is guaranteed to be zero. The simulation results are shown in Figure 11. it shows considerable torque ripple reduction by the new method. The v_{qls} trace is listed here to show that smaller voltage steps are used to produce the low index reference. And this is the direct cause of the reduced torque ripple.

The boundary of the low modulation index region using the new modulation strategy follows the same conclusion made for the natural sample limit from $(0.525*v_{dc})/1.618$. Beyond this limit (m=0.649), it can no longer maintain the 1.618:1 timing ratio and cancel out low-order harmonics in dq2 plane. At this point, it requires a different modulation method for the region labeled "mid-m-index". In this region, the reference is close to the middle decagon ring in dq1 plane. The closest vectors can be used to obtain optimal torque ripple, however, this entails longer dwelling time on the vectors along the mid-decagon ring, which causes the positive peak of the dominating 3rd harmonic current in dq2 plane to be close in phase with the positive peak of the fundamental component, the resultant phase current peak value will be

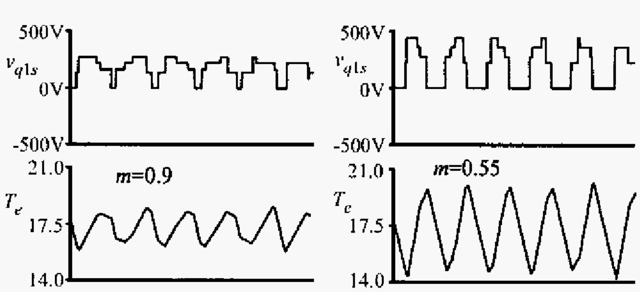


Figure 8. Natural sample modulation torque ripple comparison.

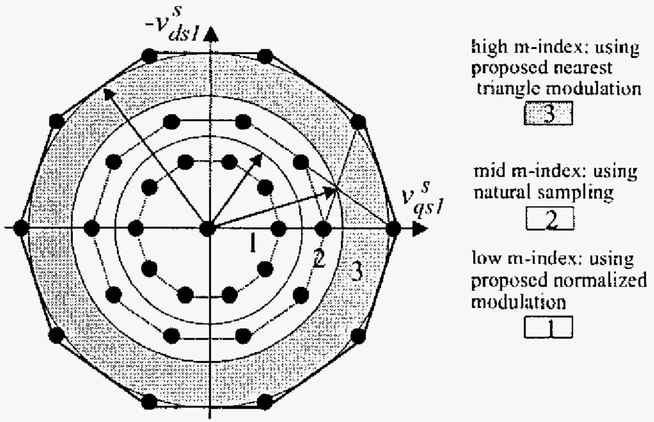


Figure 9. Three operating regions of the proposed method.

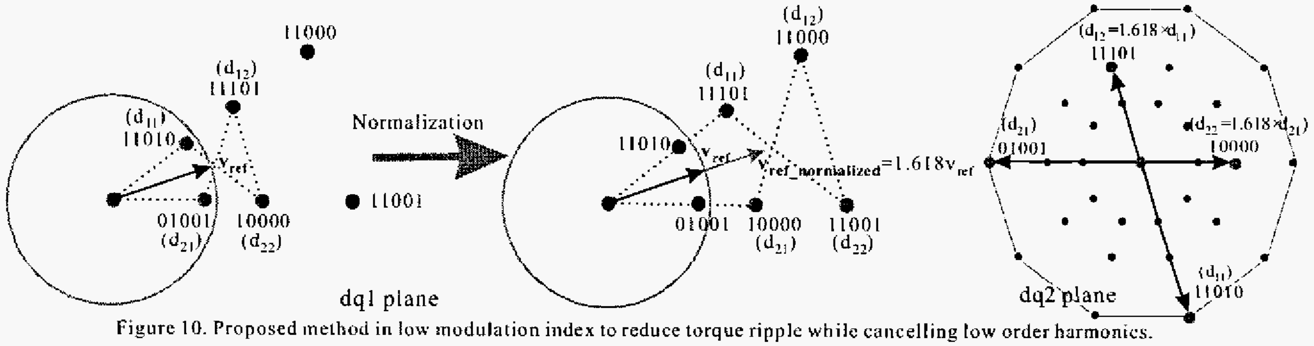


Figure 10. Proposed method in low modulation index to reduce torque ripple while cancelling low order harmonics.

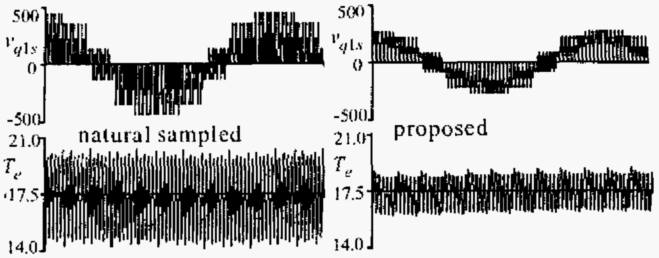


Figure 11. Simulation results comparing the proposed method to natural sampled at low modulation index .

particularly high. Therefore, in mid modulation index operation (indicated as region 2 in Figure 9), it is preferable to use natural sampling for the complete cancellation of low order harmonics.

The boundary between the mid and high modulation index can be defined at the intersection point x as in Figure 9. So the high modulation index region is $m = [0.94, 1.23]$. Any reference vector within it can be produced with the outer triangles by nearest 3 vectors, and this modulation method can be referred to as nearest triangle SVM. Although the three vectors in dq2 plane won't completely cancel each other, the harmonic current magnitude is much smaller than in lower modulation index cases, since the three vectors are mostly at the inner ring in dq2 plane. Unlike the mid m index situations, the dominating 3rd harmonics negative peak is close to being in phase with the positive peak of the fundamental, which helps to reduce the peak phase current.

The high modulation index operation region includes the part not reachable by natural sampling. So the proposed method fully uses the dc link voltage and have 23% boost in the output voltage. Compared with the SVM scheme using the "single pair of vectors" modulation which also fully uses the dc link voltage, the nearest triangle will obviously have smaller torque ripple. The performance comparison between the proposed method in high modulation index region with the natural sample modulation with the same torque output is shown in Figure 16. To further improve the performance, multi-level per phase legs are used in the 5-phase motor drive in a first published attempt to integrate these two technologies.

The proposed torque ripple reduction scheme in the high modulation index region will introduce low-order harmonics which causes extra copper loss through the stator resistance. However, for many applications including the Naval propulsion drives, it is a higher priority to have better torque ripple performance and higher dc link usage. The modulation scheme proposed in this paper makes the optimized tradeoff between the goals of minimizing the torque ripple and minimizing extra copper loss from harmonics through the whole operation range (modulation index). In the low modulation index operation, where less torque ripple is of particular interest, the method is very effective in reducing the torque ripple while totally canceling out the low frequency harmonics. These features make the proposed modulation methods a very promising option.

VII. THREE-LEVEL FIVE-PHASE MOTOR DRIVE

Although multilevel technology has been extensively studied in recent decade, there seems to be no previous research in applying multi-level to the multiphase system. By using more than two voltage levels per phase leg, the discrete steps to approximating the desired output become finer and the voltage and switching stress applied per switch is reduced. In this paper, the three-level 5-phase converter system will be introduced with the performance improvement it brings.

The topology of the three-level 5-phase motor drive and its vector plot are shown in Figure 12 and 13. Total available switching states are calculated as n^m where n is the number of voltage levels per phase and m is the number of phase legs so the above system has $3^5 = 243$ switching states. Among them, their redundancy level has single, double and triple multiplicities. Here, the vector at the origin has triple redundancy, the empty vector dots have redundancy of two and each of the rest of the vector dots represents a single switching state. It is noted that all vectors with double redundancy form a vector pattern of two-level 5-phase inverter (except for the zero vector at origin). There are totally 30 of these vectors. The total number of vectors in the plot is calculated as 243-30-2 =211.

Three-level natural sample sequence and timing appears to have no fixed pattern as seen in the two-level system, still it traverses five vectors (with one vector used twice) in each DSP cycle. However, the vector sequence (i.e. the vector path it follows) changes with different angular position. The vector path shown in Figure 14 is the combination of many different vector patterns at different angular positions. Note that the overall pattern varies with the DSP sampling frequency since it affects the angular position distribution of the sample points (simulations herein use 3.6 KHz sampling frequency). These patterns will not be shown in detail since it is not the main concern of the paper. Despite the variety of vector patterns, the timing assignment of the 5 vectors still guarantees their cancellation in the dq2 plane.

As shown in Figure 15. the nearest triangle by the enclosing

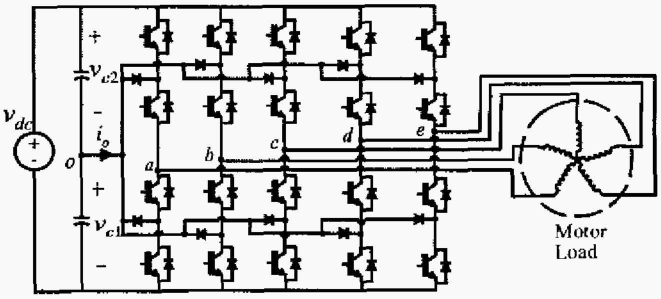


Figure 12. The three-level 5-phase inverter topology.

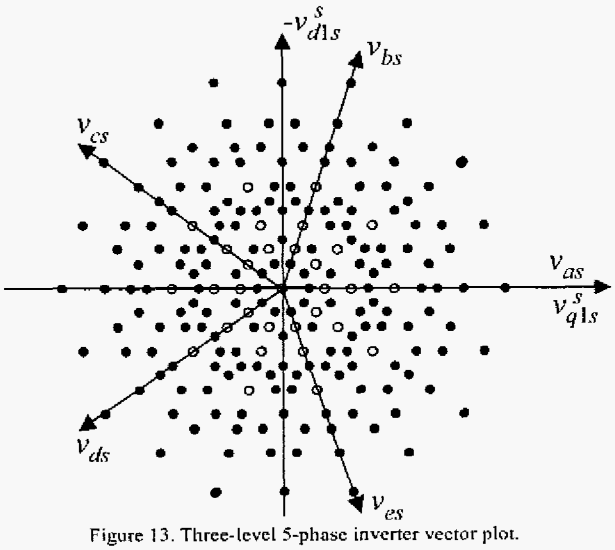


Figure 13. Three-level 5-phase inverter vector plot.

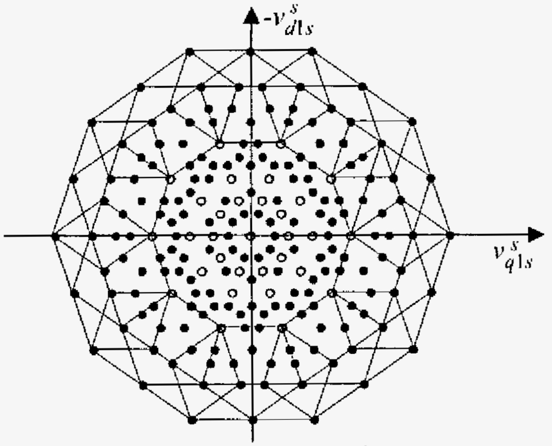


Figure 14. The natural-sample modulation vector path.

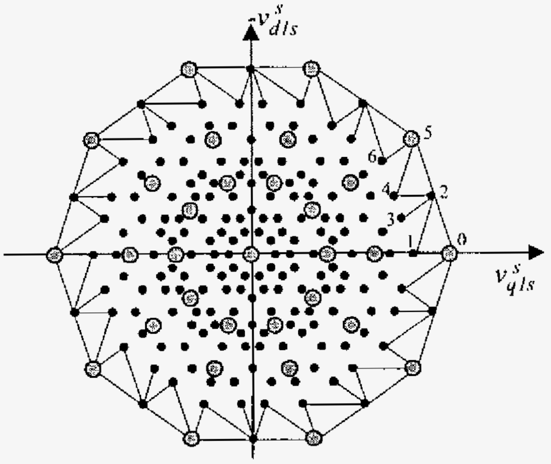


Figure 15.The nearest triangle SVM vector path.

vectors of the reference is smaller than that of the two-level system with the same dc link voltage (two-level vectors are in larger gray dots). So higher resolution and less torque ripple is expected and its torque performance is comparable to that of the system with much higher number of levels in 3-phase system. Comparing the three-level 5-phase and two-level 5-phase systems in Figure 16, it is noted that the torque ripple is reduced by half with the 3-level system.

The same figure also shows the torque output of the un-optimized switching sequence using the same modulation; its torque ripple is noticeably higher. This is due to the presence of two larger ripples, which were eliminated by rearranging the switching sequence within the DSP period. The torque ripple before and after sequence adjustment are illustrated in Figure 17. It is noted that different sequence affects the peak-to-peak torque ripple value and better sequence will more evenly distribute the vectors which tends to increase or decrease the instantaneous torque. For example, a sequence of 4 vectors (1-2-3-4), with vector 1 and 2 increasing the torque, and 3 and 4 decreasing it, can be rearranged into 1-3-2-4 to obtain smaller ripple.

Referring to Figure 15, the vectors along the outer ring of the decagon (such as 0, 2 and 5) tend to increase torque under steady state operation, while the vectors residing one layer inside (such as 1, 3, 4 and 6) tend to decrease it. By rearranging the sequences from 1-2-3 to 1-3-2 and from 3-2-4 to 4-3-2, the highest peak get reduced by the replacing a vector that increases the torque with one that decreases it. The improved sequence shown in the paper may still not be optimal and this is an area for future research.

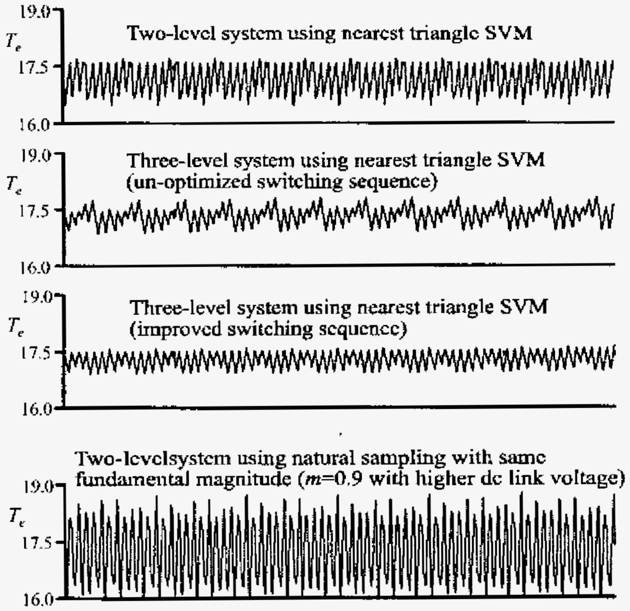
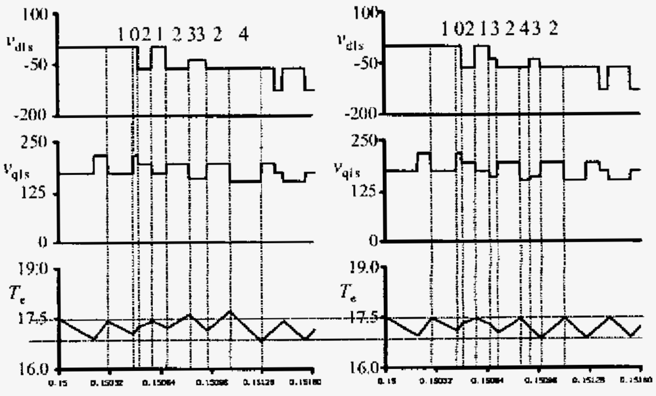


Figure 16. The torque ripple simulation results of various modulation methods.



Original un-optimized sequence

After sequence change

Figure 17. Optimizing switching sequence to reduce torque ripple.

In three phase system, the harmonics THD is used as the hallmark for choosing the optimal switching sequence, where the switching sequence affects the amount of high frequency harmonics peak value in a similar fashion. As mentioned previously, in 5-phase system, the THD is replaced by torque ripple peak-to-peak value. In both cases, the optimal switching sequence adds up discrete vectors in a smoother fashion, so the fast average voltage (for 3-phase) or torque (for 5-phase) is approximated without large steps.

VIII. APPLICATION TO HIGH POWER DRIVES

In high power applications, the PWM frequency switching poses difficulties in terms of electromagnetic compatibility (EMC), switching loss and overshoot damping. The cascaded-hybrid topology is recommended as shown in Figure 18, where two two-level inverters are cascaded through the open neutral of an induction motor. The upper high power (IGCT) inverter switches at the fundamental frequency and the other low-power

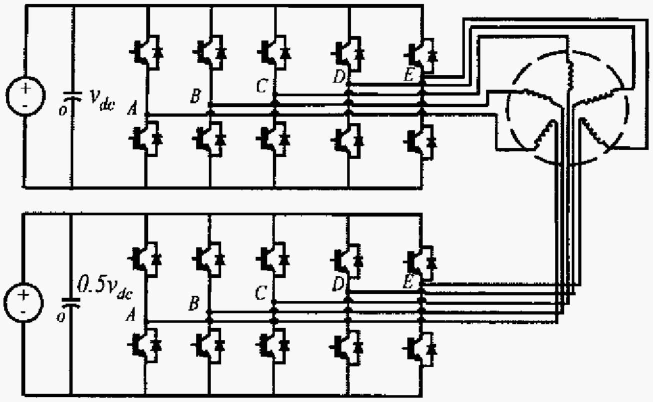


Figure 18. Five-phase cascaded motor drive topology.

inverter switches at the PWM frequency. The distinct features of this topology are:

1. Equivalent four levels per phase leg (and thus even better torque ripple performance)
2. The voltage ratio of upper and lower inverter should be maintained at 2:1 for maximum number of voltage levels
3. Reduced amount of switches and no need for capacitor balancing (as with the three-level inverter)
4. The lower dc source can possibly be a capacitor in future implementation

Finally, a brief discussion is given on motor selection considerations in high power application. The simulation results and conclusions made from this 3.7-kW motor (see appendix for its parameters) can be safely extended to motors with much higher kW rating, as seen by a few large motor cases in [8].

To achieve an even better tradeoff (than the simulation results herein) between torque ripple and harmonic current, it is advised to select (or custom make) the motor with larger leakage inductance. The small loss of effective flux linkage and the torque output by having larger leakage inductance might be well compensated by the fact that the dc link voltage usage can be boosted by 23% using the nearest vector modulation in high modulation index. The rated phase current is directly proportional to the ratio of kW rating versus voltage rating; while the harmonics current in the dq2 plane is in direct proportion to the terminal voltage rating of the motor (The dc link voltage is applied through the inverter to the low impedance circuit in the dq2 plane). For the motor with given kW rating, it is advised to use lower DC voltage level if there is such option, so that the harmonics current will be even smaller in proportion to the fundamental current.

IX. CONCLUSION

This paper has contributed a comprehensive discussion on the VSI driven multi-phase induction motor. In a 5-phase system, the phase voltage/current THD is no longer a relevant indicator for torque performance. In the context of multiple d-q planes transformed from multi-phase motor/inverter models, various modulation methods are analyzed and evaluated in terms of their torque ripple performance and harmonic control. It is pointed out in this paper that the modulation with minimized torque ripple induces harmonics of different magnitude and phase angle for different modulation index so the whole range is divided into three parts and an individual control method is proposed for each part. As a result, the optimal torque ripple is obtained in the full operating range while keeping the harmonic current within the acceptable limits.

To further improve the performance, multilevel technology is introduced into the multi-phase drive system. It is shown that the torque ripple benefits accordingly from the abundance of the vectors in three-level 5-phase system. The relation between switching sequence and torque ripple is also introduced and an initial solution provided. Finally, a hybrid-cascaded 5-phase drive topology is proposed for high power motor drive application. And motor selection considerations are suggested.

APPENDIX

The four-pole 5-phase induction motor used in the simulation is rated 230-V, 3.7-kW and it operates at 1750 rpm with 60-Hz excitation frequency. The machine parameters are listed in the table below.

Induction machine parameters.	
$poles = 4$	$M = 104\,\text{mH}$
$r_s = 0.7\,\Omega$	$L_{ls} = 5.73\,\text{mH}$
$r_r' = 0.627\,\Omega$	$L_{lr}' = 4.64\,\text{mH}$

REFERENCES

[1] H.A. Toliyat, "Analysis And Simulation of Five-Phase Variable-Speed Induction Motor Drives Under Asymmetrical Connections," *IEEE Transactions on Power Electronics*, volume 13, number 4, pages 748-756, July 1998.

[2] H. Xu, H.A .Toliyat, and L.J. Petersen, "Five-Phase Induction Motor Drives With DSP-Based Control System," *IEEE Transactions on Power Electronics*, volume 17, number 4, pages 524-533, July 2002.

[3] L. Parsa and H.A. Toliyat, "Five-Phase Permanent-Magnet Motor Drives," *IEEE Transactions on Industry Applications*, volume 41, number 1, pages 30-37, January/February 2005.

[4] H.A. Toliyat, L.Y. Xue, and T.A. Lipo, "A Five Phase Reluctance Motor with High Specific Torque," *IEEE Transactions on Industry Applications*, volume 28, number 3, pages 659-667, 1992.

[5] S.D. Sudhoff and J. Alt, "Control Of A 15-Phase Induction Motor Drive System," *Proceedings of the Naval Symposium on Electric Machines*, pages 103-110, July 1997.

[6] Y. Zhao and T.A. Lipo, "Space Vector PWM Control of Dual Three Phase Induction Machine Using Vector Space Decomposition," *IEEE Transactions on Industry Applications*, volume 31, number 5, pages 1100–1109, 1995.

[7] K.N. Pavithran, R. Parimelalagan, and M.R. Krishnamurthy, "Studies on Inverter-Fed Five-Phase Induction Motor Drive," *IEEE Transactions on Power Electronics*, volume 3, number 2, pages 224–235, 1988.

[8] P.C. Krause, O. Wasynczuk, and S.D. Sudhoff, *Analysis of Electric Machinery*, IEEE Press, 1995.

Shuai Lu received BSEE degree from the Chongqing University, China in 1997; and the MSEE degree from the University of Wisconsin - Milwaukee in 2003 and is now pursuing a Ph.D. degree at the University of Missouri - Rolla. His research specialty is power electronics and machine drives. Contact: sl4xf@umr.edu.

Keith A. Corzine received the BSEE, MSEE, and Ph.D. degrees from the University of Missouri - Rolla in 1992, 1994, and 1997 respectively. He taught at the University of Wisconsin - Milwaukee from 1997 to 2004 and is now an Associate Professor at the University of Missouri - Rolla. His research interests include power electronics, motor drives, Naval ship propulsion systems, and electric machinery analysis. Contact: Keith@Corzine.net.