Space-Shifted Split-Phase High-Speed Motor / Converter Topology with Fault-Tolerance Capability

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***Abstract*— A novel motor/converter system topology is presented, which is ideal for high-power, high-speed motor applications, especially in the case of utilizing permanent magnet synchronous AC motors. The proposed system utilizes space-shifted, split-phase, motor stator configuration, with a modular converter topology. The stator winding configuration allows the harmonic current from the different phases to cancel each other out, while maximizing the fundamental space vector. Hence, the proposed topology does not require the high-frequency PWM normally needed to reduce the time domain harmonics found in the phase currents. The switching frequency of the power converters can actually be as low as the fundamental frequency, which significantly reduces the switching losses, associated EMI mitigation, and cooling challenges. The modularity of the proposed topology also simplifies overall system design and manufacturing, provides redundancy and inherent fault-tolerance. In this paper, the system topology and control strategy are discussed. Simulation and FEA results are presented to illustrate the harmonic cancellation and other advantages of the proposed topology. Experimental results also confirm the validity of the proposed system topology.**

I. INTRODUCTION

High-speed pumps and centrifugal compressors, typically running from 5,000 to 25,000 rpm, can be found in many applications; such as natural gas pipelines, petroleum refineries, sub-sea wells, chemical and power generation. For a long time, gas or steam turbines were the only viable prime mover for these high-speed applications. However, electric driven solutions are now gaining more and more attention because of both environmental and economical reasons [1-4].

Conventional electric driven solutions require a step-up gearbox to match the motor shaft speed to the driven load speed requirement. Recent developments in high-speed motor and drive technology have made possible directly coupling electric motors to driven loads, without needing a gear box in between. Also, a reduction in the size and weight of the motor is achieved due to the increased shaft speed of the directly coupled drive train [5-13]. Eliminating the gear box from the drive train not only reduces system capital and system maintenance costs, but also increases the system efficiency by about 2%.

Running at higher speeds significantly reduces the size and weight of the motor, which permits a much tighter integration of the motor and compressor to the point where they can both share the same pressure vessel, thus eliminating external gas seals. The additional application of magnetic bearings completes this paradigm shift by accomplishing a compact, fully integrated, oil-free, seal-less, and hence low-maintenance compressor drive systems [5]. The significant reduction in size also allows the electric motor to fit better onto existing compressor skids and act as a drop-in replacement for the gas turbine, without costly infrastructure upgrades. This is particularly attractive for the system operator trying to upgrade or retrofit compressor stations already in service.

Also, having a high speed motor/drive solution opens up the door to integrating the, smaller in size, high speed motor onto existing gas turbine driven compressors, hence creating a hybrid drive system. The prime mover would remain the gas turbine, and the electric high speed motor would operate in torque assist mode, providing additional torque onto the shaft when the gas turbine is maxed out on power and an additional flow command comes in from the pipeline operator. This allows for maximizing the operating efficiency of the compressor, especially when the gas turbine output power is limited in the months of summer. This hybrid drive train also opens up a multitude of new operating modes and creates significant flexibility for the pipeline operator.

High power variable speed drives are constrained by the excessive drive losses. These losses are due to the fact that medium voltage semiconductor devices are used for switching several hundred amps of current, few times per fundamental cycle. This issue is exacerbated in high speed drives where the fundamental output waveform frequency is higher than 100Hz. Power electronics drives with standard topologies often hit a physical limit where the output can not be increased any further due to the excessive switching losses in the semiconductors. The higher switching frequency requirement also introduces EMI problems, complicated cooling schemes and additional motor insulation stress that can affect the motor life if not addressed properly.

Other system challenges for high speed and high power converter systems include the requirements of maximizing on the size and weight reduction that is achieved in the high speed motor. This means that other system components have to match the reduction in size and weight trait that the motor has. This is especially important for off-shore platform or ship board applications, and is applicable to the power electronics AC drive, as well as any other system auxiliaries such as cooling skids.

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High-speed electrical motor systems also face market penetration challenges. Being a new technology, it needs to achieve the reliability and availability required to gain the acceptance of the conservative oil and gas industry, where the cost of lost production is tremendous.

A novel motor/converter topology which is ideal for high-speed, high-power motor applications is presented. The new space-shifted, split-phase, stator topology, with modular converters can significantly reduce the required switching frequency and associated switching losses, while still maintaining lower flux harmonics in the air gap of the motor. The modularity of the proposed topology also simplifies the system design, provides redundancy and inherent fault-tolerance. Simulations are conducted to prove the effectiveness of the proposed system topology. A small scale prototype is also built and tested, experimental results validate the conclusions.

II. PROPOSED MACHINE/CONVERTER SYSTEM TOPOLOGY

The characteristics required in high speed electric drive systems (motor/drive) can be summarized as follows:

- The power electronics drive and the high speed electric motor have to be integrated together for total system optimization.
- The system has to be modular for both motor and drive.
- The system has to be fault tolerant, i.e. over sized and redundant.
- Reduced switching frequency should be adequate without having any adverse effects on performance and operation.
- Reduced size package and foot print.

In most power electronics drive systems, PWM is used for generating ac output voltage waveforms from a dc bus. In order to reduce the current and voltage harmonics generated from PWM switching, the switching frequency needs to be much higher than the output frequency, usually more than 10 times higher. This poses special challenges for the high-speed motor drive system. For example, a 4-pole, 15,000 rpm motor requires a 500 Hz fundamental frequency, which requires a much higher switching frequency than the conventional 60 Hz power converter. Increasing the switching frequency will significantly increase the switching losses and hence lower the system efficiency. The extra power loss also requires complicated cooling systems for the heat to be removed.

One effective way to reduce harmonics without significantly increasing the switching frequency is to use a specialized stator winding configuration that allows cancelling the harmonics inside the stator. Space-shifted, split phase, winding topology has been proven to cancel the effects of phase current harmonic components in diode rectifiers used in generator applications. The same proven topology is extended and used in motor applications [14-16].

In a conventional three-phase electrical machine, fractional pitch, distributed stator winding is normally used to have a sinusoidal back EMF. The winding of each phase occupies $\pi/3$ electrical angle per pole. The corresponding number of slots (N) covered by each phase is calculated by

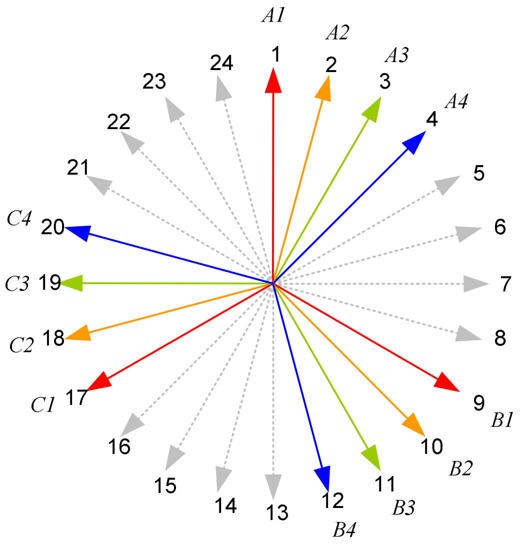

Fig. 1. Proposed winding structure.

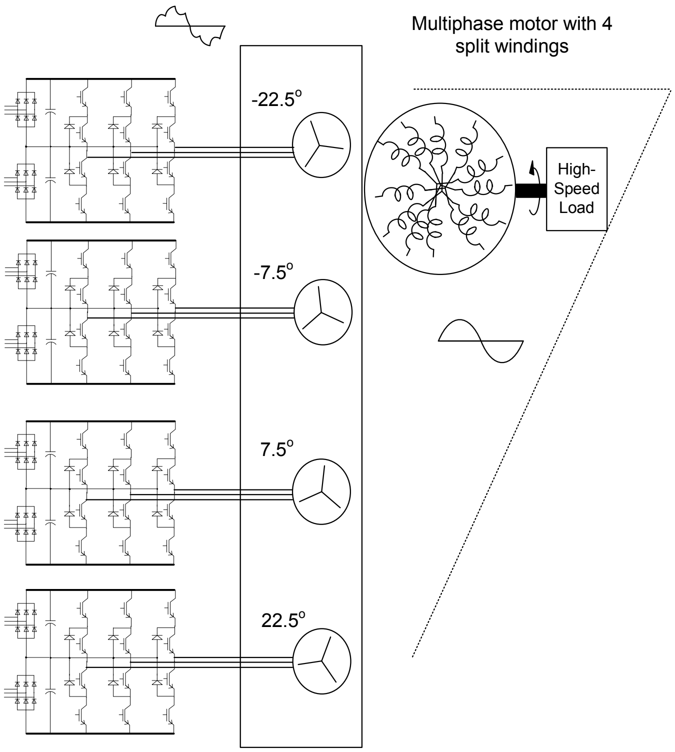

Fig. 2. Proposed converter/machine system topology.

$$N = S/3p\,, \tag{1}$$

Where S is the total number of stator slots and p is the number of poles on the rotor. The electrical phase shift θ_e between adjacent slots is calculated by

$$\theta_e = p\pi / S\,. \tag{2}$$

Instead of using all N slots for one phase winding, as in the conventional stator structure, the proposed stator configuration splits the N slots separately. Hence, N phases are inserted in those N slots (A_1, A_2, A_3 … A_N), respectively. The stator is now

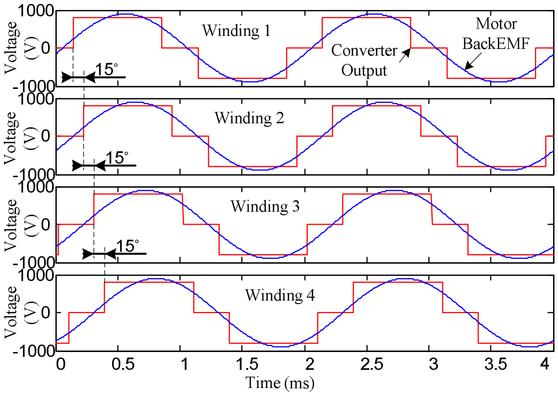

Fig. 3. Synchronization between three phase winding sets.

made up of N independent sets of three phase windings; each winding set is comprised of a single or multi turn coil running in full pitch. Fig. 1 shows the proposed winding structure for a 24 slot, 2 pole stator. Since each phase occupies 4 slots per pole, the proposed stator has 4 sets of three-phase windings. For example, phase A of winding 1 occupies slots 1 and 13, and phase A of winding 2 occupies slots 2 and 14 and so on. The electrical phase shift between the winding sets is 15°, for $N = 4$.

Fig. 2 shows the proposed system topology where N equals 4. The motor has 4 independent, space-shifted, 3-phase windings; each set has a phase shift of -22.5°, -7.5°, 7.5°, and 22.5°, respectively. The windings are connected to and powered by independent 3-phase converters. Three level converters with independent dc links are proposed here. This allows for switching frequency reduction down to the fundamental frequency.

This system topology has significant advantages when it comes to high speed, medium voltage, and high power motor drive applications. The main advantages include:

- Harmonic Cancellation
  - Allows for higher harmonic content in the stator currents, therefore reducing the requirements on the switching frequency of the converter;
  - Switching frequency can be as low as the fundamental frequency;
  - No external filters are required;
- Modularity
  - Simplifies design and manufacturing;
  - Avoids complicated device configurations i.e. parallel or series;
  - Provides fault-tolerance and redundancy;
- Higher Torque Density (5%)
- Higher Voltage Utilization of the Converter (10%)

III. HARMONIC CANCELLATION

The main advantage of the space-shifted, split-phase, stator is its ability to cancel out magnetic flux harmonics with the appropriate synchronization in place; that is to keep the triggering signal for the switching devices in each converter synchronized with the phase difference of the corresponding winding. The harmonic cancellation concept works for both induction and synchronous machines. Permanent magnet synchronous motors are used as examples in this paper, since they offer more advantages in high speed applications, when compared to other motor types.

Fig. 3 shows the line-to-neutral voltage waveforms of the space-shifted, split-phase, stator driven by three-level converters. The sinusoidal waveform represents the backEMF voltage of each winding and the staircase waveform represents the output voltage of each converter. Because of the zero voltage vector output capability of three-level converters, the switching device in each converter only needs to switch once per fundamental cycle to generate the output waveforms shown in Fig. 3. However, if a conventional two-level topology is used, the switching frequency needs to be at least three times that of the fundamental, so that zero vectors can be added to adjust the amplitude of the output voltage.

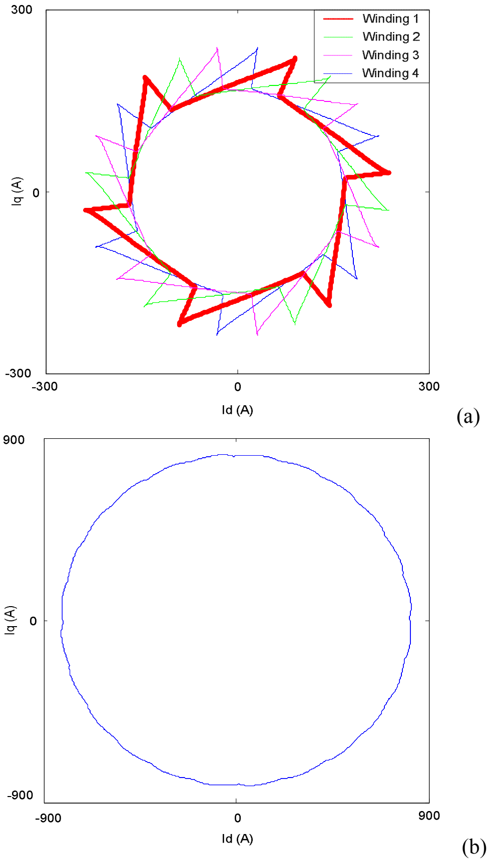

Fig. 4. *d-q* frame currents,(a) individual windings, (b) total effective.

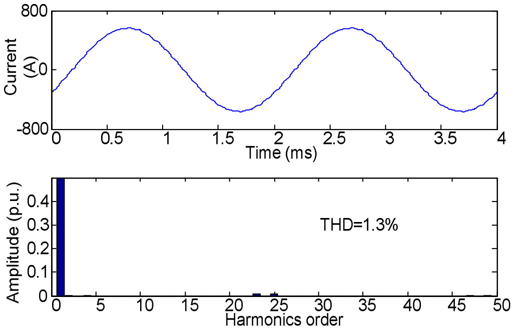

Fig. 5. Total effective stator current.

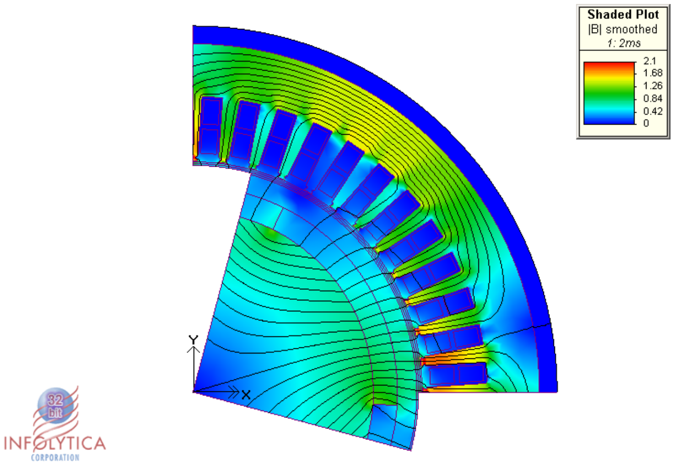

Fig. 6. 2-D FEA model of a PM, surface mount, synchronous machine.

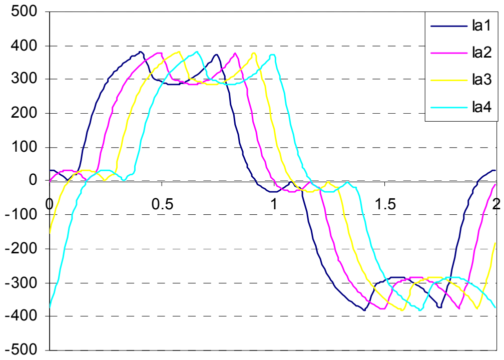

Fig. 7. Current waveforms under full block operation.

It can be seen in Fig. 3 that the backEMFs of adjacent windings have 15° phase difference. Accordingly, the triggering signals and output voltage of the converters also have 15° phase difference. Since a square waveform is used to drive the motor, there will be significant time domain harmonic components in the phase currents, as shown in the stator d-q frame currents in Fig. 4(a). The stator current for each winding has significant six-pulse current components, which would normally induce torque ripple and rotor eddy losses.

Because of the symmetry of the system, the current waveforms of all the windings are identical, with the same 15° time difference in between, as shown in Fig. 4(a). Since the six-pulse current waveforms of all winding are 15 degree off each other, the harmonic components will cancel each other out when they are summed up in the stator; the total equivalent stator current is shown in Fig. 4(b). The current trace is very close to a circle with very low 24-pulse components. This means a sinusoidal time domain current waveform with little harmonic components, as shown in Fig. 5.

Fig.5 also shows the spectrum of the total current. It can be seen that the 5th, 7th, 11th, 13th, 17th, 19th harmonics have been effectively cancelled out, and hence the lowest order harmonic in the air gap flux will be the 23rd. The only harmonic components left are $24k\pm1$, which are negligible. The THD of the effective current is only 1.3%. Therefore it is possible to avoid excessive switching losses in the medium voltage switching devices by switching at the fundamental frequency, while still maintaining machine performance equivalent or better than the one achieved by high switching frequency capable drives.

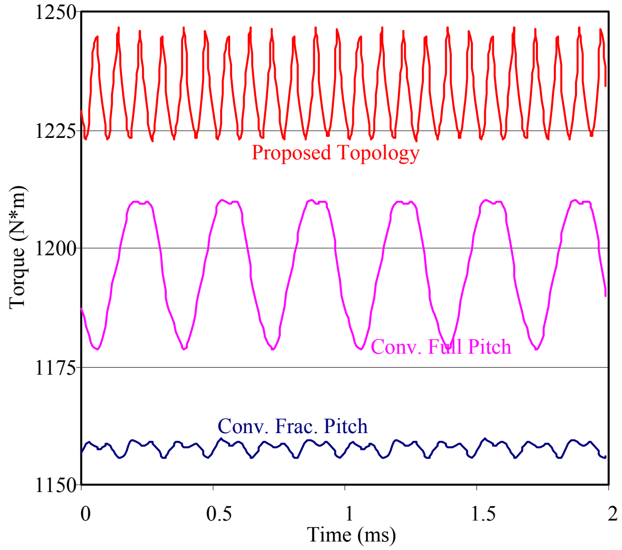

Fig. 8. Torque waveforms for different stator topologies.

IV. FINITE ELEMENT ANALYSIS

In order to further validate the performance of the proposed topology. A 2-D finite element analysis (FEA) model has been constructed and used to simulate the system. Fig. 6 shows the FEA model used. The FEA is based on a 4 pole, 48 slot laminated stator, which is equivalent to the 2 pole / 24 slot design that was discussed earlier. There are 4 slots per phase per pole, and the phase difference between two adjacent slots is 15°. Because of the machine symmetry, only a quarter of the machine is modeled to reduce the needed calculation time.

The machine is driven by four three-level voltage source converters. The voltage sources used to drive the machine are chosen as such to have the phase current in phase with the backEMF, therefore generating maximum torque for the given current. Even though there are mutual couplings between the coils, they do not affect the symmetry in the phase currents, because the mutual inductance values are also symmetrical. The current waveforms are shown in Fig. 7.

The electromagnet torque is calculated and plotted in Fig. 8. The top trace shows the resulting torque of the proposed topology. The torque is ripple is 0.62% of the average value. Considering the high harmonic content in the phase currents, the torque ripple value shows that the harmonic cancellation works effectively. The RMS current for each coil is 254.4 A, with 23.3% THD.

Conventional winding topologies are also modeled based on using the same stator lamination. One is using the full pitch winding, the other is 5/6 short-pitch winding, where each coil covers 10 instead of 12 slots. For both cases, sinusoidal current sources, simulating high PWM switching frequency operation, were used to drive the motor.

When the fractional pitch windings are used to reduce the flux harmonics in the air gap, the torque will also be reduced by the pitch factor, 0.966, for a 5/6 pitch winding, which can be verified by the torque waveform shown in Fig. 8. The

TABLE I. COMPARISON OF DIFFERENT WINDING TOPOLOGIES

	Full pitch Conventional Winding	5/6 pitch Conventional Winding	Proposed Winding Topology
Voltage source	Sinusoidal	Sinusoidal	Square wave
Current	250 A	250 A	254.4 A
THD of Current	0	0	23.3%
Torque	1196 N.m	1158 N.m	1230 N.m
Torque ripple, rms	1.14 N.m	11.5 N.m	7.6 N.m
Torque ripple, %	0.09	0.99	0.62
Torque per A	4.78	4.632	4.83

torque generated by the full pitch winding is 1196 N.m, while the short pitch winding generates only 1158 N.m of torque. However, the short pitch winding does reduce the torque ripple generated by the harmonics in the space flux distribution, from 0.99% to 0.09%.

In the conventional motor, all the coils for the same pole and the same phase are connected in series. Since the voltage vector from one coil to the next are displaced from one another due to the position of the slots. The total voltage is smaller than the arithmetic sums of the individual voltage values, and the ratio is defined as the distribution factor. The distribution factor for the 48 slots, three phase winding is 0.958. For the proposed topology, since each winding is a full pitch / concentrated winding, it would further increase the torque density by about 5%, when compared to other winding configurations.

On the other hand, the torque density is also affected by the time domain harmonic components in the phase currents. In the previous section, it has been shown that the harmonic components of the phase winding currents do not induce harmonic flux in the air gap. However, the harmonic currents do increase the phase current without generating any active torque, therefore, potentially reducing the overall torque density. Using the current waveform shown in Fig. 7 as an example, where the RMS value of the current is 254.4 A, and the THD is at 23.3%, therefore the fundamental component for the current is 247.4 A.

Despite the fact that harmonic components in the phase currents reduce the torque density, this effect is compensated by the concentrated winding effect. Therefore, the proposed topology still has a higher torque density when compared to the conventional full pitch and fractional pitch winding. A detailed comparison between the proposed topology and conventional topologies is listed in Table. I.

V. FAULT TOLERANCE

A Simulation model of the proposed motor topology is constructed. For simplicity of illustration, an ideal model is chosen, where iron saturation, slot effects, asymmetry between phases, and harmonics flux distribution along the air gap are ignored. The motor model consists of 4 independent windings; each one is based on the conventional permanent magnet synchronous motor model. The currents of all winding are transformed into the same stator reference frame and summed together. The electromagnetic torque is calculated based on the currents in the stator stationary *d-q* axis and fed to the mechanical equation.

Fig. 9 shows the simulation results. The top figure shows the currents for each winding. The middle figure shows the equivalent current. Since the flux harmonics cancel each other out, there are little harmonics left in the equivalent current. The harmonic cancellation concept also works in other winding configurations and stator laminations. For example, it is also possible to have two windings with 30° phase shift in between or three windings with 20° phase shift in between, and so on. The higher the number of windings used, the better harmonic cancellation is achieved. For example, for a two winding configuration, the lowest harmonic left is the 11th, and the THD of the equivalent current becomes 4.3%. If a three winding configuration is used, the lowest order harmonic left is the 17th, and the THD of the equivalent current becomes 1.7%.

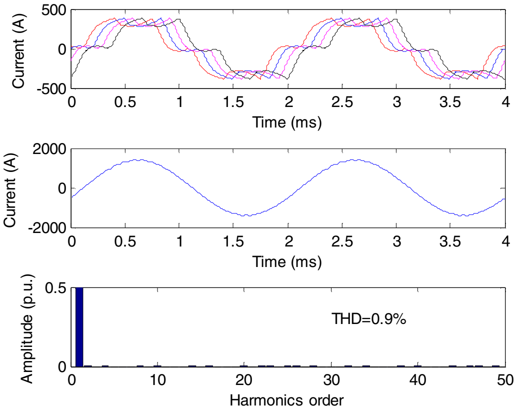

Fig. 9. Simulation results showing the harmonics cancellation effect.

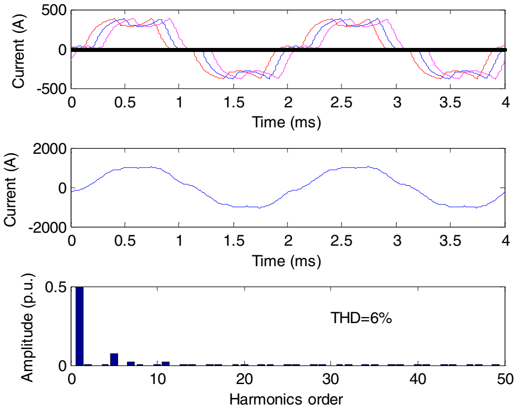

Fig. 10. Simulation results with one failed winding.

In the conventional system, if there is a fault, in either the converter or the winding, the system would have to shut down and faulty parts need to be replaced. In the proposed modular system, inherent fault tolerance and redundancy is achieved. The system can continue running at a reduced power level in the case of fault regardless of the fault location. The higher the number of windings used not only helps harmonic cancellation, but also improves the inherent fault tolerance. For example, if a two winding configuration is used and one winding or converter fails, the system can still run at half power. For the four winding configuration we have discussed before, the system can still run at 75% of the original output power.

TABLE II. FAULT TOLERANCE FOR DIFFERENT NUMBER WINDINGS

Number of Windings N	Lowest Harmonics	Effective THD	Capacity with N-1 Windings	Effective THD with N-1 Windings
1	5th	23.5%	0	n/a
2	11th	4.3%	50%	12%
3	17th	1.7%	67%	7.9%
4	23rd	1.0%	75%	6%
5	29th	0.6%	80%	4.7%

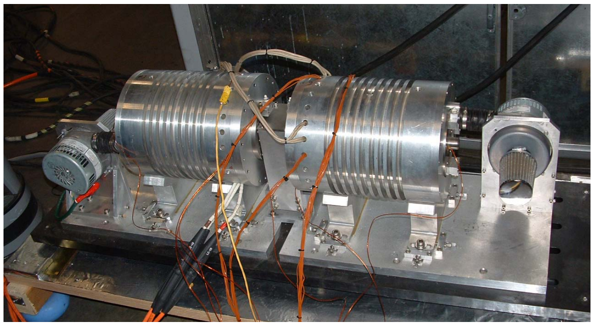

Fig. 11. Experimental motor-generator test setup.

Fig. 10 shows the simulation results with one winding failed and turned off. Because of the asymmetry introduced in the phase currents, the harmonic cancellation no longer eliminates all lower order harmonics. The equivalent current now has 6% THD, still reduced from the 23% THD in each phase. The detailed comparison of fault tolerance operation for different number of winding is shown in Table II.

VI. EXPERIMENTAL RESULTS

In order to validate the system concept and simulation results, a scaled-down 50 kW, 30 krpm, back to back motor-generator test setup is built. The motor is configured with the proposed multiple space-shifted, split phase, winding structure (N=4). The generator used is a conventional three phase fractional-pitch winding generator. It is connected to a three phase ac load bank to provide a controlled load. A picture of the test setup is shown in Fig. 11.

The stator of the motor has 24 slots and 2 poles. It consists of 4 sets of 3-phase windings. Each winding set has 3 phase single-slot, full-pitch, windings occupying 6 slots total. Each winding set is rated at 400 V and 12.5 kW at 500 Hz (30 krpm), i.e. total rating of 50 kW at 500 Hz, 400Vll. The motor is powered by 4 two-level converters sharing the same dc bus. Since two-level converters are used, SVM is used to adjust the amplitude of the output voltage; therefore the IGBTs have to switch at least three times per fundamental cycle. The system control is implemented on a National Instruments PXI real-time controller with the FPGA module to guarantee a perfect synchronization of the gate signals for the different converters. Figs. 12 and 13 show the experimental results of the system running at 9000 rpm and 15.5 kW. Fig. 12 shows the phase currents for the different windings. It can be seen that the shape of currents are very close to each other and there is a 15° time delay between one phase current and the next. The spectrum of the phase current is also shown in Fig. 12. Because of the six-step operation, the phase currents have significant low older harmonic components, including the 5th and 7th. In this case, due to the relatively low motor impedance and light load, the THD of the current is as high as 56%. However, in the total effective current, all harmonics below the 23rd are effectively eliminated, as shown in Fig. 13. Based on the analysis in the previous section, the remaining harmonic components are 23rd, 25th, 47th, and 49th. Since the 47th and 49th harmonics are negligible in the phase currents, the only harmonics left in the stator are the 23rd and 25th. Hence, the THD dropped significantly from 56% in the individual phase currents to 3% in the total effective machine current.

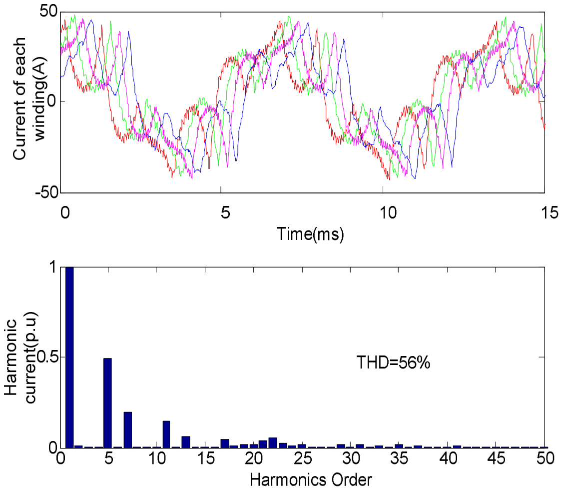

Fig. 12. Phase A currents for all windings and current spectrum.

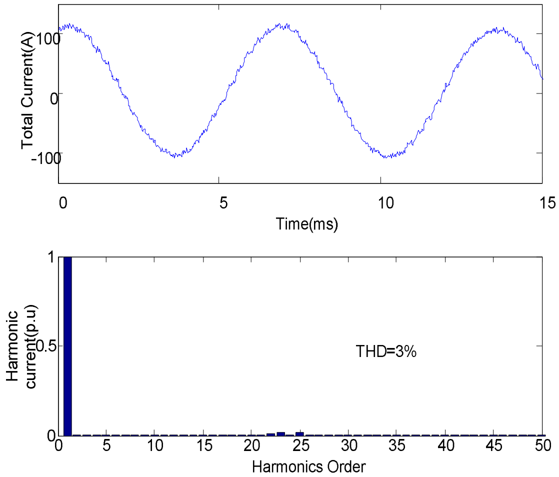

Fig. 13. Total effective current in the stator and its spectrum.

Figs. 14 and 15 show the experimental results of the system running at 9000 rpm and the same 15.5 kW load with one converter turned off. Fig. 14 shows the phase currents for the different windings. Because of the higher load per winding, the THD of the current is slightly reduced, when compared to the same load condition with all four winding sets in operation.

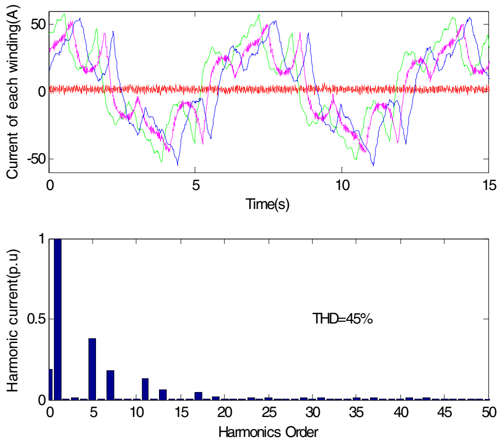

Fig. 14. Phase A currents with one failed windings and current spectrum.

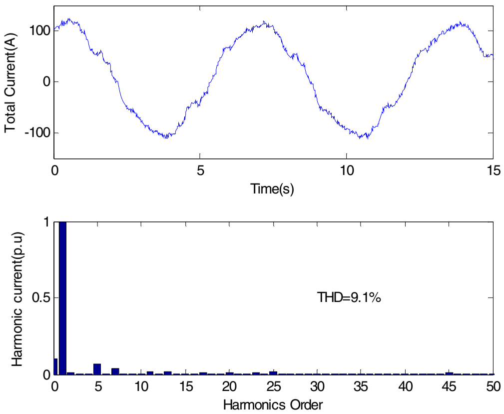

Fig. 15. Total effective current in the stator and its spectrum.

VII. CONCLUSION

A novel motor/converter topology is proposed. The proposed topology is based on space-shifted, split-phase, stator winding configuration, fed by modularized converter sets. With the appropriate control scheme, time domain harmonic components of the different phase currents are cancelled out. Therefore, the switching frequency of each converter can be as low as the fundamental frequency while still maintaining a sinusoidal flux distribution in the air gap. The modularity of the proposed topology also simplifies the system design and provides redundancy and inherent fault-tolerance. Other benefits include higher torque density, and higher dc bus utilization. The proposed system topology is a perfect candidate for high-speed, high-power, electrical drive systems, especially for the case of permanent magnet synchronous motors, where the rotor needs to have minimal eddy current losses and hence minimal thermal growth, which could adversely affect the rotor dynamics. The proposed topology is cost effective when compared to conventional electrical, high speed, drive systems that utilize a gear box and a variable speed drive for process regulation. The proposed topology also opens the door to designing very compact, high speed, high power, motors with a high pole count and still being able to drive these motors with cost effective power electronics solutions that are off-the-shelf.

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