On-Board Electrical Network Topology Using High Speed Permanent Magnet Generators

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***Abstract*—A zonal dc electrical distribution system topology is presented for on-board applications. The system is based on using high speed permanent magnet synchronous generators driven by gas turbines as prime movers and DC distribution with local conversion at the load points. Proposed permanent magnet generator design and construction, system topology and evaluation are given. A scaled down experimental test set up is described in this paper.**

***Index Terms*—DC power systems, Electrical networks, high speed, Marine electrical equipment, On-board generation, Permanent magnet generators, Rectifiers, Synchronous generators.**

I. NOMENCLATURES

PM; Permanent Magnet,
PEBB; Power Electronics Building Blocks,
IPT; Inter Phase Transformer,
EM; Electromagnetic,

II. INTRODUCTION

Conventional electrification systems used for on-board applications such as ships, marine platforms, transportation or aviation have been primarily AC based, whereby conventional prime movers such as diesel engines have been used to directly couple to low speed synchronous generators. System improvements have been achieved by using gas turbines as prime movers, thus improving environmental compatibility and reducing the size and weight of the prime mover. In such systems the gas turbine would have to be coupled through a speed reducing gear to the low speed conventional generator.

Further system improvements in terms of size and weight have been shown by eliminating the gear box unit and directly coupling the gas turbine to a matched high speed generator. Different candidates exist for high speed generators that utilize different operation and construction principles such as PM synchronous generators, wound rotor synchronous generators, solid rotor induction generators and high temperature super conducting generators. Different studies have been done on developing criteria for finding the optimal selection for the given power and speed range [1], where it is stated that PM generators are well suited for high speeds, i.e. greater than 10,000 rpm and power levels up to 8 MW from a power density point of view. PM generators are a suitable candidate for generation applications. This is due to the readily available magnetic field on the rotor, simplified generator control and possibility of using simple three phase diode bridges for AC to DC conversion, without the need for active rectification units. Hence, allowing for the benefits of DC distribution network topologies.

High speed PM synchronous generators are typically classified based on rotor construction; such as axial or radial gap PM generators. Radial gap PM generators are much more suitable towards higher power ratings from a rotor dynamics stand point. Radial PM generators are grouped into surface mount or embedded magnet generators. Surface mount PM generators are more cost effective and simpler to manufacture than embedded magnet based generators.

Surface mount PM generators use a sleeve to provide the required containment and a solid rotor core, or hub, provides the radial stiffness.

Different sleeve structures are used for containing the magnet pieces at the high rotational speeds, these sleeves or membranes are either a high strength nickel based alloy or a composite carbon fiber material [2].

The high-speed, sleeved (surface mount) PM generator has an intrinsically larger magnetic air-gap than the un-sleeved PM generator due to the sleeve thickness and the increased magnet thickness required to force an equivalent amount of flux through the larger magnetic gap. This larger magnetic gap provides better demagnetization protection under short-circuit conditions.

By utilizing magnetic bearings, the generator maximizes the benefits of a lube-free system. In addition, magnetic bearings can operate at higher speeds with less loss than certain types of mechanical bearings.

High speed PM generators allow for a reduced system weight, higher operating efficiency, reduced maintenance costs and a smaller envelope than a conventional solution in the same power rating. However, with the higher power density and frequency also comes higher power loss density. Special attention must then be paid to the choice of lamination material, coil construction, and cooling mechanism for what would otherwise be a typical stator and housing design. In the case of a high speed PM generator, temperature sensitivity of the magnet material is an additional factor. For this reason, Samarium Cobalt is often the choice to realize higher temperature designs.

In order to minimize the losses in high speed generators, active high frequency rectifiers are often used which are costly, bulky and generate higher losses due to the higher switching

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frequencies required. Using passive rectifiers is normally a challenge; due to the significant generator losses caused by the time harmonics in the phase currents, predominantly, the 5th and 7th components.

In this paper, a PM generator is presented, which has *N* sets of full pitch, three phase, space-shifted, split-phase windings for allowing connection to *N* passive three phase rectifiers, while keeping the machine losses to a minimal by achieving harmonic cancellation in the air gap of the machine.

Fig. 1 shows available ratings of gas turbines taken from an in-house market survey; the triangle shown encompasses the majority of these ratings. It can be seen that a power of 8 MW at 15,000 rpm would be a good fit for a PM generator selection to operate with these different gas turbines. The proposed machine ratings are given in Table I.

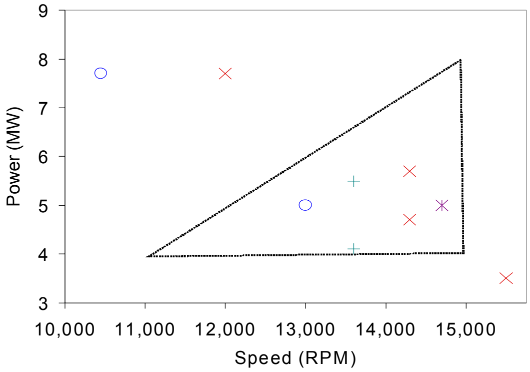


Fig. 1. Gas turbine ratings from various manufacturers. The triangle shows the target area for a product family rated at 8 MW and 15,000 rpm.

TABLE I
REQUIRED SPECIFICATIONS FOR A HIGH SPEED MEDIUM VOLTAGE GENERATOR

Item	Specification
Power Rating	8 MW
Pole/Phase	4/3
Rated Speed	15 krpm
Over speed	18 krpm
Magnetic Bearing Configuration	2-Radial, 1-Thrust
Sleeve Configuration	Wound carbon fiber
Cooling Configuration	Water/Glycol stator jacket Curtain air flow over end-turns

III. GENERATOR DESIGN AND DEVELOPMENT

A. Electromagnetic Losses

Relatively thin, low loss silicon steel is used to contain losses under the high-frequency operation. Special care must be taken in selecting the strand configuration in the multi-strand, multi-turn form-wound coils to minimize strand losses under high-frequency operation. Commercially available, lumped-parameter, circuit simulators with core loss and copper eddy loss models were used to predict stator losses. These calculations were compared to the results obtained with a commercial electromagnetic finite element analysis (FEA) software and published, closed-form, analytical methods.

Rotor losses due to eddy-currents were predicted using a time-stepping, rotating-grid solver from the same commercial FEA software. The solution was obtained with a two-dimensional analysis that ignored the axial segmentation of the magnets and the electrical isolation between each other and the shaft. This approach overstates the losses, which were found to be insignificant when compared to the rotor windage loss.

B. Rotor Containment

A finite element analysis tool is used to recreate the winding process of the rotor with carbon fibers in a polyetheretherketone (PEEK) matrix, including the effects of rotor temperature, as a time dependent variable, carbon fiber tension, and winding feed rate. Random generation of the rotor geometry node by node according to the manufacturing tolerances creates a more realistic system model.

The model static stresses found are input to a stress analysis tool to model the dynamic stresses in the rotor during operation. The rotor is modeled at nominal operating speeds at varying temperatures as well as at the over-speed condition under varying temperatures.

This model is then verified by rotor burst testing. The rotor burst testing results, coupled with tensile strength tests conducted on wound rings of the carbon fiber, determine the material stress limits and therefore, the final dimensions of the required rotor containment sleeve.

C. Rotor Dynamics

A commercially available FEA rotor dynamics software package is used to analyze the free-free natural frequencies and mode shapes of the generator. The solution approach of the tool is to lump the mass and inertia of a defined area to create the nodes. The nodes are connected by mass-less beams. The magnetic bearings are modeled as dynamic supports with variable stiffness and damping. The magnetic bearings used in this generator consist of two radial support bearings, one to either end of the shaft and a separate active thrust bearing at the coupled end to compensate for any axial loading. A coupling appropriate to the generator size was chosen and is modeled as a cantilevered weight.

The total rotor weight is over 2,000 lbs and the bearing span is ~62 inches. This resulted in a first forward bending mode close to the maximum operating speed of the generator. Therefore axial stiffening is added to the rotor resulting in a first forward bending mode of 21,029 cpm, which is 17% above the allowed generator over speed of 18,000 rpm.

D. Cooling

Loss breakdown is given by the electromagnetic modeling tool discussed above. A lumped parameter model is used to model the generator geometry including rotor, stator, and cooling jacket to determine the correct mass flow required to maintain a max temperature of 150°C at 40°C ambient per coil insulation and carbon fiber.

A separate aluminum cooling jacket with a press fit to the stator back iron pulls out heat through a water/glycol cooling flow. Curtain-air flow pulls heat out of the end turns, also air is forced through the mid stack and it exists through the end turn housing on either side of the generator. This air is required for cooling the air gap and the tooth tips of the stator.

IV. WINDING STRUCTURE AND EM MODELING

In a conventional three-phase synchronous generator; fractional pitch, distributed stator windings are normally used. Each phase winding occupies $\pi/3$ electrical angle per pole. The corresponding number of slots (N) covered by each phase is calculated by

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

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 in the conventional stator structure, the stator configuration, proposed for the electrification system presented in this paper, splits the N slots separately. Hence, N phases are inserted in those N slots ($A_1, A_2, A_3 \ldots A_N$). The stator is now made up of N sets of three phase windings; each winding set is comprised of a single or multi turn coil running in full pitch on the stator. Fig. 2 shows the proposed winding structure for a 48 slot/4 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 slot 1, 13, 25, and 37, and phase A of winding 2 occupies slot 2, 14, 26, and 38, and so on. The electrical phase shift between winding sets is 15°, for $N = 4$.

The net result of this winding configuration is to have harmonic cancellation in the stator iron and in the air gap such that the 5th and 7th harmonic components in the phase currents would not have an impact on the generator from an iron loss and torque ripple stand point. The first non-cancelled harmonic components in the air gap flux are at ($6N \pm 1$). Fig. 3 shows the basic harmonic content of a three phase rectifier current and the associated equivalent waveforms for $N = 1$ (conventional) and $N = 4$. It can be seen that although each phase current still has significant harmonic content, the harmonic cancellation in the stator results in a sinusoidal equivalent current. All harmonics below the 23rd are effectively cancelled out. Fig. 4 shows the net magnetic flux density in the air gap including the effect of slot current time variation for the case of having $N = 1$ with fractional pitch coils and $N = 4$ with full pitch coils. The thickness of the curve represents the flux ripple that the rotor sees and consequently rotor losses in the sleeve, magnets and hub. The high flux ripple induces higher eddy current losses in the magnets and hub. It can be seen that the flux ripple is significantly reduced for the case of $N = 4$.

2D FEA modeling is done for comparing different generator stator winding configurations. The configurations modeled are $N = 1$ fractional pitch winding, $N = 1$ full pitch winding, $N = 2$ full pitch winding and $N = 4$ full pitch winding arrangement. Torque ripple and losses in the hub and magnets in the rotor are plotted for comparison in Fig. 5. It can be seen that the reduction in torque ripple and losses in the rotor are significant with $N = 4$.

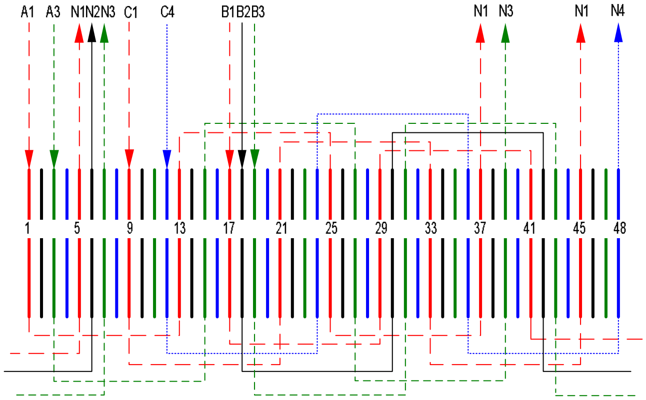


Fig. 2. Winding proposal for N=4, 48 slot stator, 4 pole generator, where A1 phase starts in slot1, A2 phase starts in slot 2, A3 phase starts in slot3 and A4 phase starts in slot 4…etc.

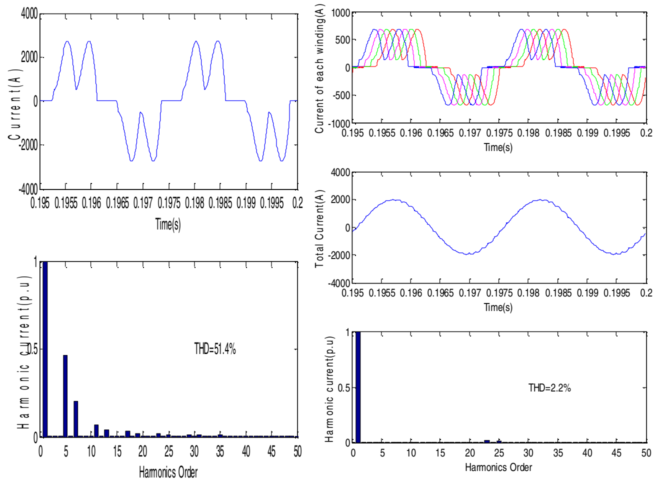
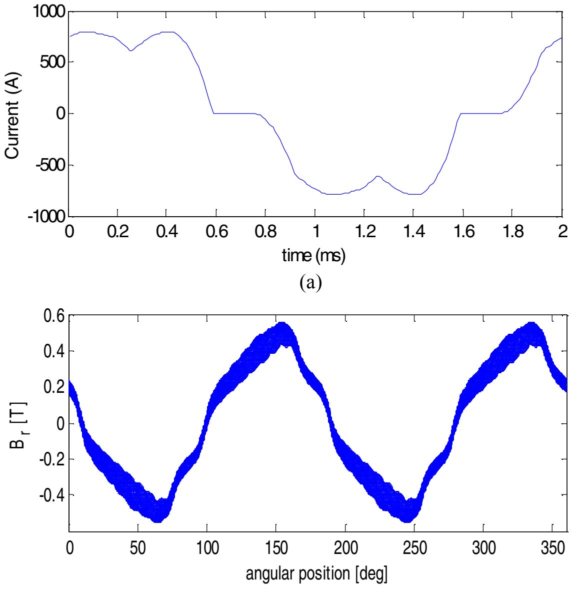


Fig. 3. Effective THD comparisons for the case N=1 and N=4.



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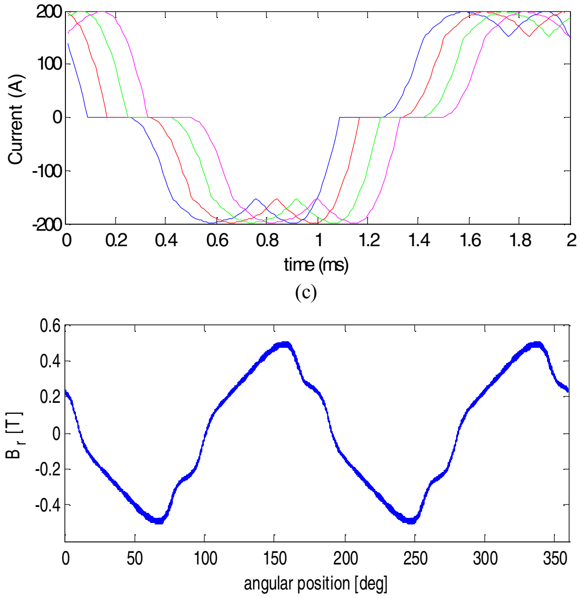
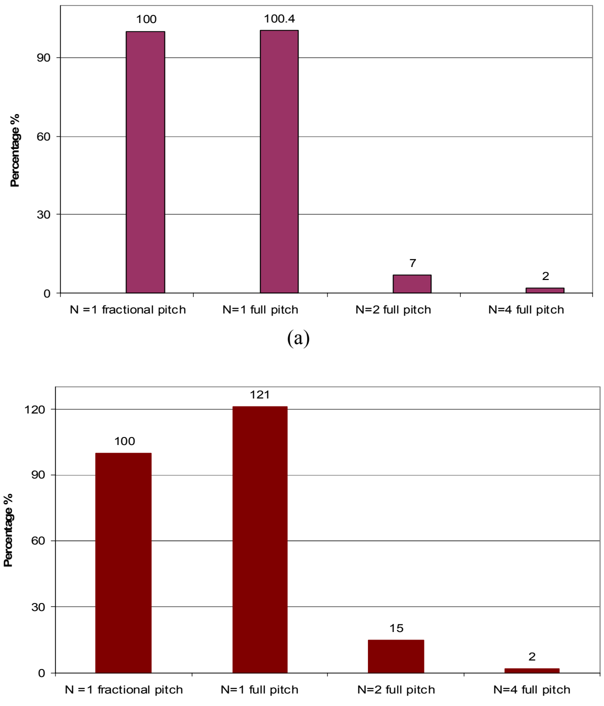
(b)



(c)

(d)

Fig. 4. Total synchronous frame flux density in the air gap with line currents, N=1 (a) and (b), N=4 (c) and (d).



(a)

(b)

Fig. 5. (a) Hub losses with different winding configurations, base is the value for conventional fractional pitch three phase winding set, (b) Peak to Peak torque ripple, base is the value for conventional fractional pitch three phase winding set.

V. PROPOSED NETWORK TOPOLOGY

The proposed electrical network is comprised of two primary gas turbines directly coupled to individual 8 MW, 15,000 rpm, 48 slot stator and 4 pole rotor PM synchronous generators. The stator is wound with space shifted, split phase, winding arrangement, as described previously, and each three phase winding set is feeding a passive three phase rectifier bridge, the output of the bridges are connected in parallel and are feeding a common dc ring. The dc distribution ring is divided into zones and each zone can be isolated allowing for the network to be reconfigured as need be.

Ship service loads are fed through step down transformers and sinusoidal filters from each independent zone, hence giving isolation and limiting ground current interaction with the rest of the system, they can also be fed from a different zone in case of a failure. Emergency backup generator set is used with similar topology, for example 1 MW running at 15,000 rpm and configured for $N = 4$.

Fig. 6 shows the proposed electrical network for on-board applications with $N = 4$ on the PM generator unit. The rectifier bridges consist of fast recovery diodes in order to be able to handle the high fundamental frequency of the machine (500 Hz), the power rating of each rectifier block is rated power divided by N. For $N = 4$, the units can be air cooled or liquid cooled and can be packaged into the generator housing. Thus allowing for a compact medium voltage dc generator with integrated protection, switch gear and DC interface bus bars. Protective devices are coordinated as such to be able to isolate a faulty segment or zone with minimal degradation to the overall system. The presented topology is comparable to the US Navy's electric ship Integrated Power System (IPS) that is being developed for the DD(X) next generation navy ships program [3].

Proposed system highlights are discussed below:

1) Optimized stator size that is not required to handle harmonic losses typical when having passive rectifier line current waveforms. With minimal harmonic coupling/ heating into the rotor.
2) Eliminates the need for high speed active rectifiers; thus, saving on cost, size and weight, weight reduction can be higher than 90% when going from active to passive rectifiers. Also, eliminates the need for AC-DC PEBB on the load converters since dc distribution is used, which would give on average 30% to 40% further reduction in weight/size for the AC propulsion drives.
3) Passive rectifiers typically have high availability, are maintenance free, require no feedback or control as opposed to active rectifiers, hence high system reliability/ survivability and lower running costs are achieved.
4) Higher system efficiency as opposed to active rectification systems, passive rectifiers are roughly 2% higher efficiency that active rectifiers, which translates into better overall fuel efficiency.
5) Wider prime mover speed range allowed while maintaining controlled output at the load point converters.

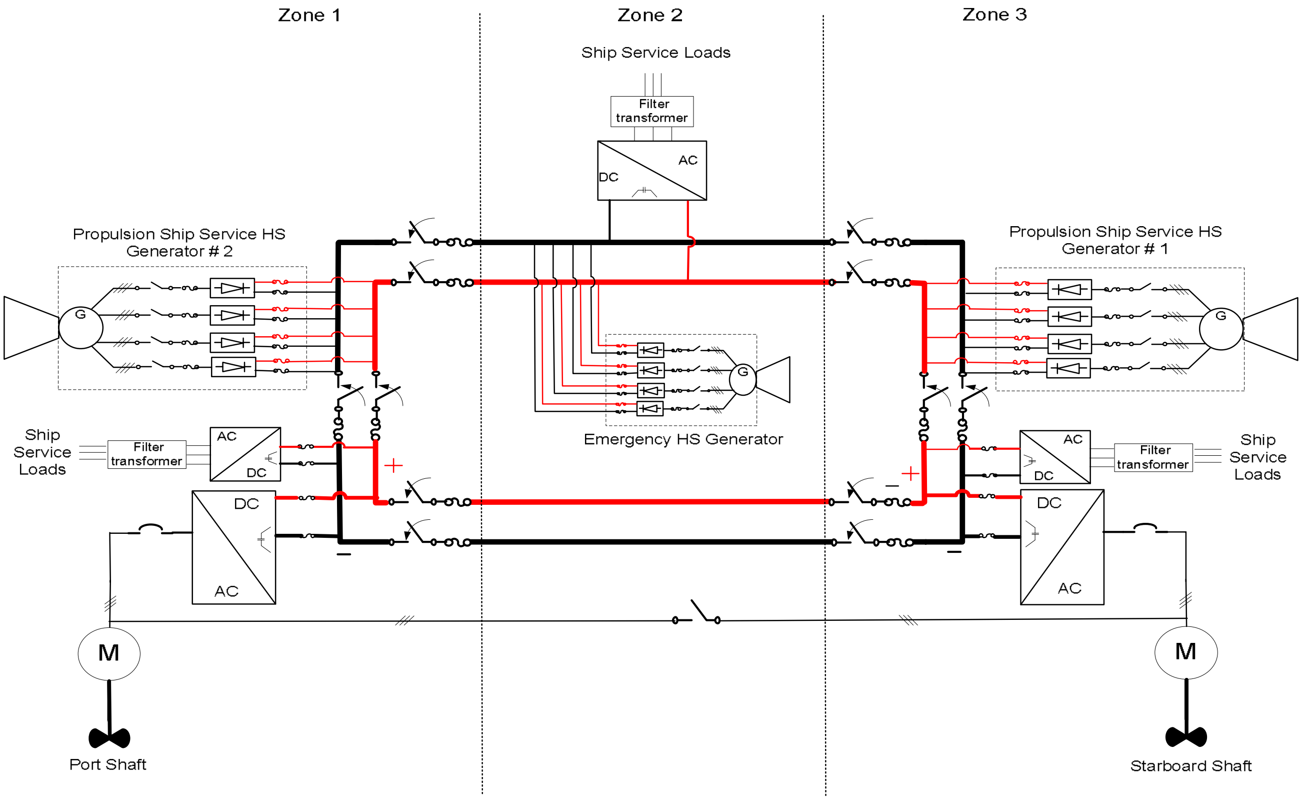


Fig. 6. Proposed Zonal DC distribution network based on high speed PM synchronous generators and passive rectifiers.

6) Inherently a fault tolerant system; this is due to the redundancy (*N* rectifiers) and through over rating can lead to higher system availability (*N*+1).
7) Transformer-less electrical network topology. No need for IPTs to reduce current ripple in the system. This is shown in Fig. 7 where dc current is shown for different cases of back EMF waveforms and with/without IPTs. Also, the network topology does not require any isolation transformers since the neutral points of each winding set is isolated from each other.
8) Simplified grounding schemes with minimal neutral point voltage shifting between the generators in the system, this alleviates the need for special control or filtering schemes as discussed in [4].
9) Voltage control and load sharing on the dc ring can be achieved by having an upper level control system issue a master slave command to each turbine/generator unit or by having voltage droop control on each load point converter, such control strategies are discussed in [5].
10) As a result of zonal generation, distribution and intelligent power system management, single point failures will have limited negative effect on system performance since the system can be designed in such a way that enables automatic bypass of the degraded section.
11) Voltage ripple frequency on the main dc link will be at ($6{\cdot}N{\cdot}f_{max}$) where f_{max} is the maximum output frequency of the generator, this would normally be in the several kHz range for a high speed generator, in this case 12 kHz, thus, improving the quality of the dc link without the need for high frequency switching IGBTs or any filtering requirements.

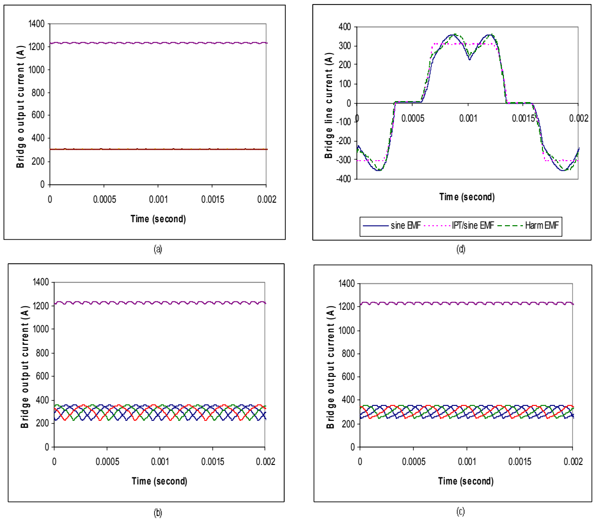


Fig. 7. (a) Total load current for R load and individual bridge dc current for a system using IPTs, (b) Total load current for R load and individual bridge dc current for a system without IPTs and sinusoidal back EMF, (c) Total load current for R load and individual bridge dc current for a system without IPTs and actual back EMF, (d) Line current for sinusoidal back EMF without IPTs, sinusoidal back EMF with IPTs and actual back EMF without IPTs.

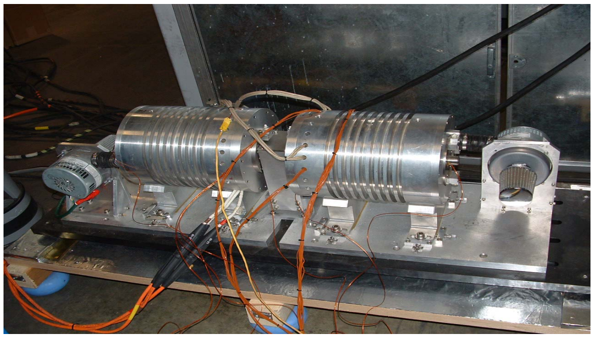
VI. EXPERIMENTAL TEST SET-UP

In order to validate the simulation results, a scaled-down 100 kw back to back motor-generator test set up is built. One stator (generator) is configured with the proposed multiple space-shifted split 3-phase winding structure, the second stator (motor) is built with conventional fractional pitch winding ($N = 1$). The stators have 24 slots and use a 2 pole PM incanel based metal sleeved rotor. The electrical phase shift between adjacent slots is 15°, which is equivalent to the simulated 48 slot, 4 pole case. The stator of the generator consists of 4 sets of 3-phase windings. Each winding set has 3 phase single-slot full-pitch windings occupying 6 slots. Each winding set is rated at 400 V and 25 kW at 500 Hz. The pictures of the stator at different production stages are shown in Fig. 8.

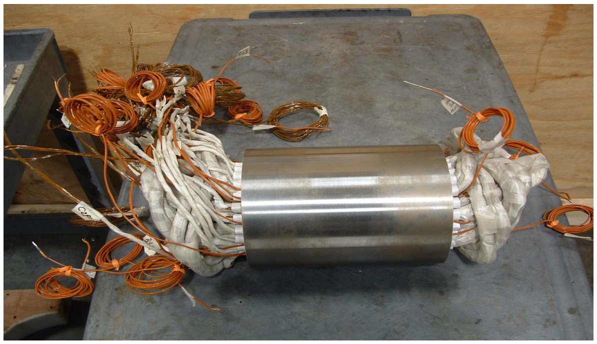
It can be seen in the pictures that the stator configured with split phase winding structure has longer end turns than the conventional fractional pitch stator. The difference though is less than half an inch in this case, and the new stator, with the longer end turns, was still within the dimensions allowed to be mounted in the same housing as the conventional stator.

Each three-phase winding set is feeding a three-phase diode bridge rectifier, each with a low inductive capacitive dc link. The outputs of the four rectifiers are tied together into one common dc bus and connected to a dc load bank. The stator is equipped with several thermocouples for the temperature to be measured and recorded at different locations such as the slot back iron and tooth tip.

An average value for the rotor temperature is interpolated from the open circuit back EMF measurements. With samarium cobalt magnets, the open-circuit back-EMF will drop by 0.4% every 10°C rise. Therefore, the rotor temperature can be calculated based on the open-circuit back-EMF of the motor.



(a)



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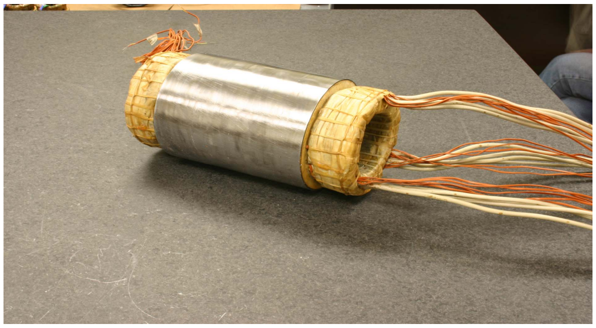

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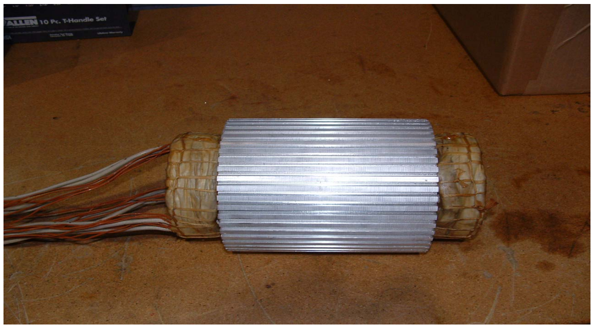

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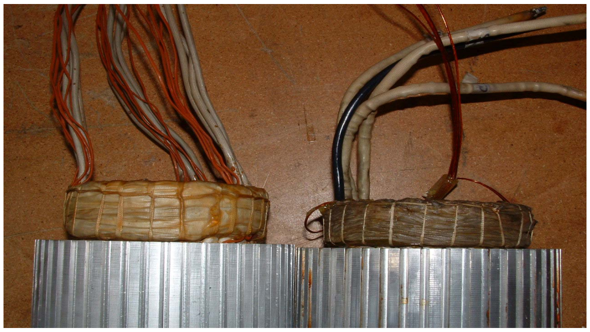

(e)

Fig. 8. (a) Back to back motor-generator test set up, (b) Split phase (N=4) stator before forming, lacing and varnish, (c) Finished stator with N=4, (d) Cooling heat sink attached to the new stator (e) conventional (N=1) stator, on the right, and new split phase (N=4) stator, on the left, shown for comparison of the end turn length.

VII. CONCLUSIONS

PM generators running at high speeds and configured with space shifted, split phase, winding sets are considered an enabling technology for zonal dc based electrical network topologies. The proposed network has inherent redundancy, allows for higher system efficiency and reduction in cost, weight and size of the PEBB by eliminating the need for active rectifiers or drive front-end requirements. Further advantages are gained such as simplifying system protection coordination and simplifying the grounding requirements, without needing extra filters and special controls in order to have balanced neutral points and no circulating currents. Full pitch coils are preferred when doing passive DC rectification since the added odd harmonics (5^{th}, 7^{th}, 11^{th} …) to the line to line voltage waveforms would increase the voltage level at the output, boast output power capability and reduces ripple in the rectifier units.

ACKNOWLEDGMENTS

The Authors wish to thank Shamim Imani, CALNETIX, for his support on the hardware set up.

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