A Reconfigurable-Winding System for Electric Vehicle Drive Applications

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Abstract- **In this paper, a reconfigurable-winding system for electric vehicles (EV) applications is discussed. It features fewer solid-state ac switches compared with state-of-the-art designs and does not have a dc circuit short-circuit failure mode. Simulation results show that the proposed design can achieve significant inverter loss reduction in low and high speed modes. Preliminary experiments demonstrate the ability to change winding configurations in about 5 ms.**

I. INTRODUCTION

Since hybrid electric vehicles (HEV) were introduced to the market in the late 1990's, high power electric machines for automotive applications have been heavily researched. While reconfigurable winding approaches with interior permanent magnet synchronous motors (IPMSMs) are discussed in this paper, this approach is applicable to almost all types of electric machines for both motoring and generating applications. Automotive manufacturers most commonly use IPMSMs for xEVs (including HEV, battery EV, and range-extended EV) because of their high efficiency and high power density despite the high cost associated with rare-earth PM materials. The efficiency map of an IPMSM for a commercial HEV [1] is shown in Figure 1.

At low speeds, motor currents can be selected according to the maximum torque per ampere (MTPA) rule so that the stator current in the motor is minimal. This keeps the switching and conduction losses of the inverter and copper losses of the motor low. As the motor speed increases above the base speed, flux weakening (FW) controls are implemented by applying larger negative d-axis currents to weaken the permanent magnet flux so that the rectified back electro-magnetic force (emf), which is proportional to rotor speed, is lower than the dc bus voltage. Since the total current from the inverter is limited, the torque-producing current in FW mode is reduced due to increasing FW current and phase impedance. This results in reduced torque as speed increases as indicated in Figure 1.

To achieve higher output power with the same motor, one possible solution is to use serial windings at low speed and then reconfigure them to parallel windings at high speed. In Fig. 2, the torque and power characteristics versus speed of an IPMSM with serial (solid lines) and parallel windings (dotted lines) are depicted qualitatively. With parallel windings, the motor's back emf is halved and the FW control is used at a

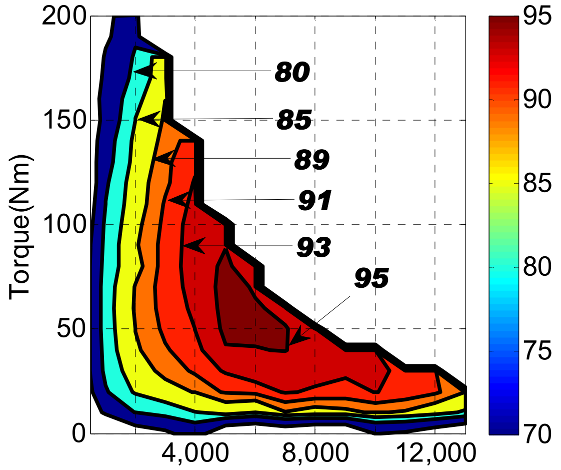

Fig. 1. Efficiency map of an IPMSM drive used in a commercial HEV [1].

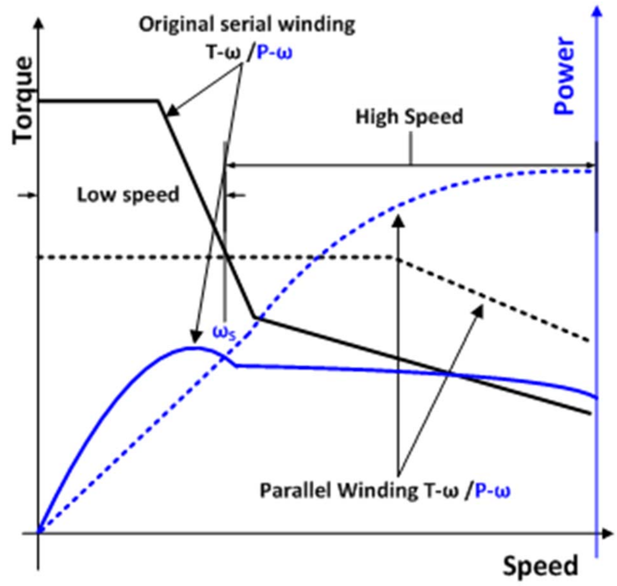

Fig. 2. Torque-speed and power-speed characteristics of a drive with serial and parallel windings.

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higher speed. This roughly increases the constant torque range by 100% and doubles speed at which peak power occurs. At the same time, the peak torque with parallel windings is roughly halved and the phase inductance of the parallel windings is about one fourth of the serial windings' inductance. At low speeds, serial windings are selected to achieve high torque output. At high speeds, parallel windings are selected to achieve higher power. This two-speed range drive will have better torque-speed (T-ω) and power-speed (P-ω) characteristics than the one speed range motor drives – i.e. fixed winding motor drives – if the windings are reconfigured properly. This can be particularly useful for alternative motor technologies without rare-earth materials as they tend to have lower power densities than that of rare-earth PM machines.

In this paper, we will discuss solutions to implement reconfigurable windings which will allow a reduction of motor size for a given power rating, an increase of motor output power for a given size, and improve system drive cycle efficiency. Also under consideration are the important impacts on system volume/cost and advantages of changing torque-speed characteristics compared with mechanical hydraulic transmissions and their peripheral components.

II. Review of Previous Work

Reconfigurable windings, also known as switchable windings, have been implemented in electric motors, and some products are already on the market. For example, some 3-phase induction motors use a star-delta soft-starter to reduce inrush currents during startup. A star winding is initially selected, which has a larger impedance and back-electromotive force (back-emf). When the motor builds up its speed and back-emf, it switches to a delta winding arrangement so that it can go to higher-speed/power operation.

Recently, more papers and patents report progress on reconfigurable winding approaches for automotive applications. For example, Eckart and Erik worked on reconfigurable windings for a surface-mounted permanent magnet synchronous motor and published several papers in the 1990's [2-3]. Chen and Cheng, by using relays, developed a motor with reconfigurable windings for electrical transmission applications and with brushless dc motors to expand the speed range [4-5]. Huang and Chang developed reconfigurable windings in an induction motor to achieve faster motor start-up [6]. Hsu, Fulton, Krieger, and Shum filed different patents recently for reconfigurable winding motors [7-9]. This approach uses ac switches to change the winding's configuration so that the motor operating mode can be changed to achieve a wider speed range and faster motor starting. Another approach uses pole-changing motors to achieve expanded operation. Most of methods under this approach are suitable only for induction motors [10-12].

Fig. 3 illustrates an important industry patent (refered to as patent A) by Hsu and Fulton on this topic. This diagram represents a system in which eight ac switches are used to change the star-connected stator windings between parallel and serial connections. In parallel mode, the five blue ac switches are on and the three orange switches are off. In serial mode, the five blue switches are off and the three orange switches are on.

The diagram in Fig. 4 represents another patent (refered to as patent B) filed in 2012 for electric bike applications. It uses only three ac switches; five less than the eight switches of patent A. In parallel mode, K_{P1} and K_{P2} are on and K_S is off. In serial mode, K_S is on and K_{P1} and K_{P2} are off. However, this system must use two small inverters instead of one. Further, all three switches must be installed in a dc bus. This arrangement may add to the total dc bus stray inductance which will in turn increase the voltage spikes on the dc bus. This makes it less suitable for high-power applications. Also note that patent B has a dc short-circuit failure mode if all three switches are accidentally on at the same time. Therefore, some extra protection should be considered.

Fig. 5 shows a recent approach by Y. Takatsuka, H. Hara, K. Yamada, A. Maemura and T. Kume [13]. It is an advancement of the early work demonstrated in [14-17]. A three phase diode bridge with one active swich (SiC MOSFET) is used to construct a three phase short circuit switch. Only two active switches are used in a two-speed range drive system, which is less than the previous approaches.

This idea was tested in a 30 kW continuous, 65 kW peak power electric drive system, achieving a peak efficiency of

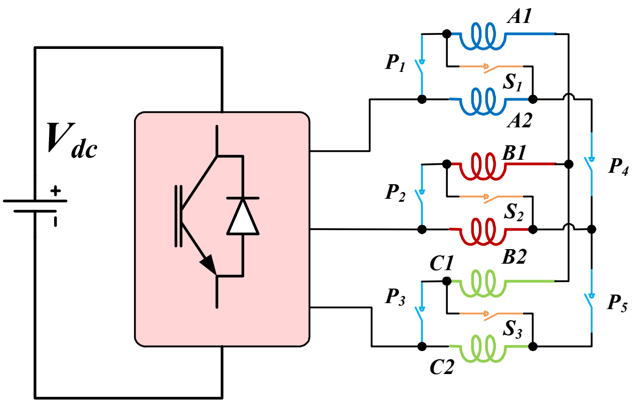

Fig. 3. Schematics illustrating Patent 20110234139 A1 (published in 2011 by Hsu).

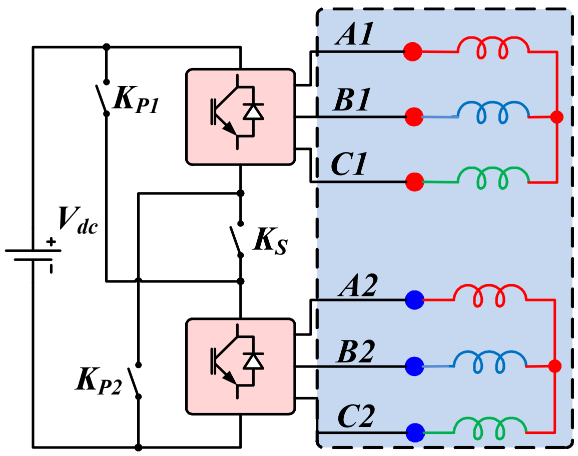

Fig. 4. Schematics of patent US20120086380 (published in 2012 by Krieger and Shum).

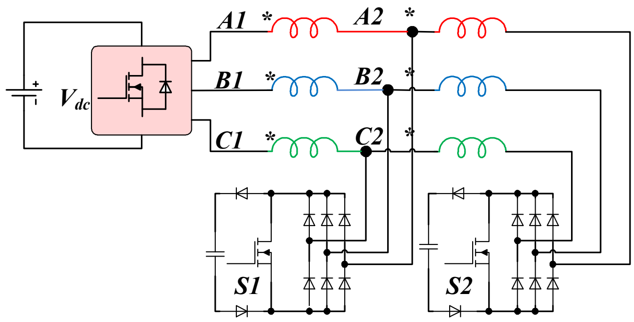

Fig. 5. Two speed range drives system proposed in [13] by Y. Takatsuka, H. Hara, K. Yamada, A. Maemura and T. Kume.

95%. An improvement of the system efficiency over the one-speed range drive was also reported. It is different from the other approaches in that, in high speed mode, only part of the windings conduct current. The other parts of the windings are inactive. There is no parallel winding configuration. This unique feature, on one hand, gives flexibility selecting the winding ratio. On the other hand, it generates higher copper losses than the serial/parallel approach due to inactive windings.

In this approach, the two three-phase diode bridge have 12 diodes generating additional conduction losses. It should be noted that the current ratings of the two active switches are higher than the motor phase current, since they must carry the rectified three phase current. Detailed loss analysis and comparisons with other schemes were not presented in [8]. Another unique feature of this apporach is that the switch-box only needs six motor winding terminals, while patent A requires 9 motor winding terminals.

Approaches based on open-end winding motors are reported in [18-20]. Two inverters have to be used for this type of approach, which may be a disadvantage.

III. Proposed Design

A new reconfigurable winding design is proposed to achieve expanded operation. The overall block diagram can be seen in Fig. 6. Instead of using one inverter to supply the total motor current, two small inverters with 50% of the maximum current of the motor are used. In serial mode, ac switches K_{S1}-K_{S3} are on and K_{P1} and K_{P2} are off; *Inv1* works and *Inv2* is off. In parallel mode, ac switches K_{S1}-K_{S3} are off and K_{P1} and K_{P2} are on; both *Inv1* and *Inv2* switch.

By introducing an optimal phase shift angle between the carriers, the effective switching frequency can be doubled and significant reductions in torque/current ripple and capacitor ripple current can be achieved compared to using a single inverter at the same switching frequency [21-22]. Compared with the approach shown in Fig. 3, the proposed design uses fewer ac power switches. Because it does not insert ac power switches in the dc bus, it does not have the dc short-circuit failure mode of the patent shown in Fig. 4.

To evaluate the advantages, the inverter losses of the design proposed in patent A were compared with those of the new approach[23]. The loss model includes both switching and conduction losses. The basic equations used to calculate switching losses and conduction losses in a 3-phase voltage source inverter can be seen in (1–3). Equation (1) shows the inverter switching losses, where f_{SW} is the switching frquency, V_{dc} is the dc bus voltage, I_{PEAK} is the peak phase current, V_{ref} and I_{ref} are the voltage and current at which the switching losses are given, E_{GT}, E_{DE} are the switching losses of the insulated gate bipolar transistor (IGBT) and the diode. For IGBTs, the switching losses include turn-on loss E_{ON} and turn-off loss E_{OFF}. For diodes, the switching losses are mainly due to the turn-off loss. Equation (2) shows the conduction losses of the IGBT, in which V_{CEO} and r_{IGBT} are the zero current saturation voltage and equivalent resistance of the IGBT, m is the modulation index, and θ is the power displacement factor. Equation (3) shows the conduction losses of the diodes in which V_{fO} and r_d are the zero current forward voltage and equivalent resistance of the diode. With Eqs. (1) to (3), the total voltage source inverter losses can be calculated. The losses associated with one solid-state ac switch for changing winding configurations are also considered in Eq. (4), where V_{CER0} is zero current forward voltage drop and r_R is the equivalent resistance of the solid-state ac switch (relay).

$$P_{SL} = \frac{6 f_{sw} V_{dc} I_{Peak}}{\pi V_{ref} I_{ref}} (E_{GT} + E_{DE}) \tag{1}$$

$$P_{CL\_IGBT} = I_{PEAK} V_{CEO} \left(\frac{1}{2\pi} + \frac{1}{8} m\cos\theta\right) + I_{PEAK}^2 r_{IGBT} \left(\frac{1}{8} + \frac{1}{3\pi} m\cos\theta\right) \tag{2}$$

$$P_{CL\_D} = I_{PEAK} V_{f0} \left(\frac{1}{2\pi} - \frac{1}{8} m\cos\theta\right) + I_{PEAK}^2 r_d \left(\frac{1}{8} - \frac{1}{3\pi} m\cos\theta\right) \tag{3}$$

$$P_{CL\_R} = I_{PEAK} \left(\frac{2V_{CER0}}{\pi} + \frac{I_{PEAK} r_R}{2}\right) \tag{4}$$

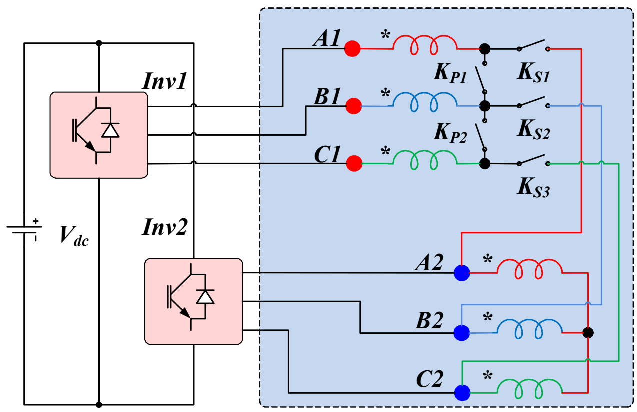

Fig. 6. Proposed switchable winding design with only 5 ac switches.

Two three phase voltage source inverter modules from Fuji Electric with same voltage but different current ratings were used in the simulation[24]. The ratings are 1200V/450A for module A and 1200V/225A for module B. IGBT A (6MBI450V-120-50 by Fuji Electric) will be used in the patent A approach while two IGBT B (6MBI225V-120-50) modules will be used in the approach proposed in Fig. 7. The same solid-state ac switch is used in the two approaches. The dc bus voltage is 650V, the peak current is 250A in parallel mode, and the switching frequency is 7.5kHz. The key parameters of the devices used in the simulation are shown in TABLE I.

TABLE I
IGBT AND DIODE PARAMETERS

	V_{CEO}/V_{F0} (V)	r_{IGBT}/r_d (mΩ)	E_{ON} (mJ)	E_{OFF} (mJ)
IGBT A	0.8	2.6	13	60
Diode A	1.15	1.56	0	33
IGBT B	0.8	6.125	5	30
Diode B	1.08	3.3	0	17.5
AC switch	0.9	2.0	0	0

Fig. 7 shows the total inverter losses of different approaches at low-speed with coil currents between 10A and 120A, including power losses of the ac switch. The trace with blue squares shows the losses of the patent A design in low-speed operation. The trace with cyan diamonds shows the loss of the proposed reconfigurable winding approach at low speed. The red circles indicate the inverter losses with fixed parallel windings. Since Patent A and the proposed approach are in serial mode, the inverter only needs to supply the coil current. On the other hand, when the inverter drives the fixed parallel winding motor it must supply 2 times the coil current which adds to the switching and conduction losses of the inverter. The proposed approach has slightly higher inverter loss (1190W vs. 1150W) because of the higher conduction and turn-on losses of IGBT B. Both can achieve a loss reduction of about 25% compared to the fixed windings parallel configuration.

In Fig. 8, the inverter losses in high-speed mode (parallel configuration) are compared with a coil current between 10A and 120A. Since two coils are in parallel, the inverters need to supply a current of 240A in each phase. The trace with red circles shows the inverter losses of a fixed windings motor at different peak phase currents between 10A and 120A. The trace with blue squares shows the losses of the patent A design. The trace with cyan diamonds shows the loss of the proposed reconfigurable windings approach at high speed.

The patent A design has the highest losses while the fixed winding motor has the second highest. This is because of conduction losses in the 5 solid-state ac switches in parallel mode. With the proposed approach, due to the effective doubled switching frequency by interleaving, the inverters can work at half of the switching frequency of the other two approaches. Additionally, it only has two solid-state ac

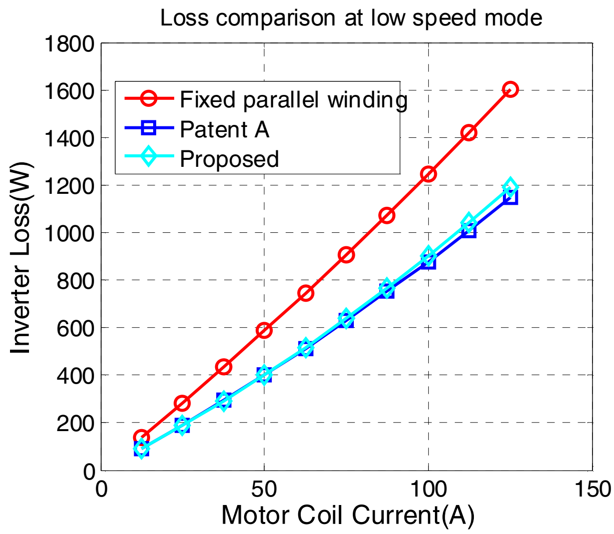

Fig. 7. Loss simulation of the proposed design, fixed windings drive, and patent A system at low speed.

switches conducting current in this mode. All these factors contribute to important loss reductions.

The proposed reconfigurable winding approach has lower losses in both low-speed and high-speed operation compared to the fixed winding motor. At high speeds, the loss reduction is about 18%. At low speeds, the reduction is as high as 25%. Compared with the patent A design, the proposed reconfigurable winding approach achieves a loss reduction of about 38% at high speed. Note that the loss at low speed is slightly higher (+4.0%) than that of the patent A approach. These results show the proposed reconfigurable winding approach can reduce power loss further than the approach of patent A. To make the comparison fair, it needs to be pointed out that the maximum inverter output current of the proposed approach is half of patent A in low speed mode. Adding six solid-state ac switches could double the current. However, the inverter losses in both low-speed and high-speed will increase.

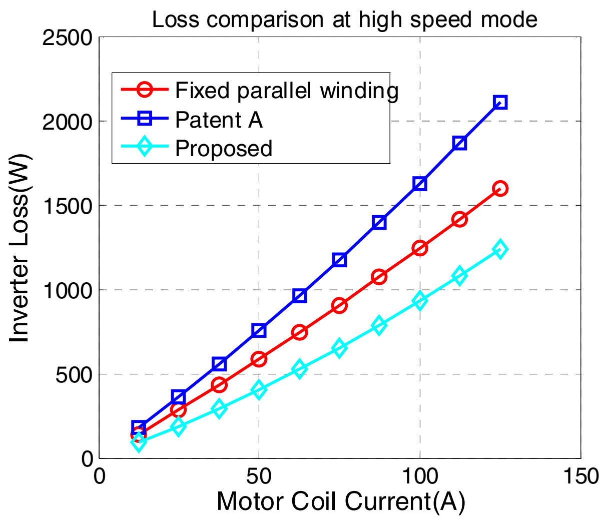

Fig. 8. Loss simulation of the proposed design, fixed windings drive, and patent A system at high speed.

IV. Switching Transient, Design of Low-cost AC Switch PCB and Benchtop Component Test

To change the windings' configuration, the drive will have some switching transients. During the first transient, the controller needs to bring all the phase currents to zero. Secondly, the ac switches will turn on/off to change the winding configuration. Finally, the controller will build up the 3-phase currents to the new operating point. This is demonstrated in Fig. 9, in which the three-phase motor current d and q axis current and electromagnetic torque are shown from top to bottom. Since all 3-phase currents are zero during the switching transient, there is an undesirable torque interruption in the powertrain. The duration of torque interruption is determined by the speed of the ac switches. If fast solid-state ac switches are used, each turn on/turn off takes only about 1~2 ms and the torque interruption time could be shorter than 10 ms. However, if slow ac switches like ac contactors are used, the torque interruption could be longer. Further, ac contactors have a limited number of operating cycles due to mechanical parts. All of these drawbacks make ac contactors unattractive for automotive applications. To minimize the torque interruption, fast and low-cost solid-state ac switches were selected in this project.

There are different ways to construct a solid-state ac switch to turn on/off windings. Using SiC MOSFET has the advantage of low conduction losses and high maximum junction temperature. However, they are used with a three-phase diode bridge [9], increasing conduction losses. Further, SiC MOSFETs are more expensive than IGBTs. Two IGTBs in anti-serial connection can also be used to construct a solid-state ac switch. However, IGBTs have the same issue of high conduction losses and high cost. In our search, we found anti-parallel thyristors are most suitable – they have the lowest conduction losses and lowest price among all candidates. On the other hand, the maximum junction temperature of thyristor is around 130 °C, which is lower than SiC MOSFET and even some IGBTs.

There are some off-the-shelf, solid-state ac switches based on thyristors already on the market. However, they are quite expensive— around $100 for a switch with a 660V/125A ac rms rating. An anti-parallel thyristor module with higher ratings of 1600V/134A ac rms costs only about $15 (for quantity >1680). It also has a smaller footprint than the off-the-shelf solid-state ac switches. Therefore, anti-parallel thyristor modules were selected to construct the ac switches in this project. It should be noted that extra gate drive circuits are needed for this module.

An HEV motor with 3-phase windings was used in the test. To simulate a switching transient, the windings were configured to a serial connection initially, then re-configured to a parallel connection. A single-phase inverter controlled by a Texas Instrument's floating-point 32 bit digital signal processor (DSP) was used for the real-time test.

Fig. 10 shows the ac switch PCB assembly and the motor winding. A 106.7mm × 109.2mm PCB was designed to switch the motor 3-phase windings as indicted in left portion of Fig. 10. At top left is the top view of the PCB and at bottom left is the bottom view. Three solid-state ac switches were installed. It may be noted that further size reduction is possible since not all ac switches are working at the same time. At right is the motor stator, which was used in a commercial hybrid EV drive system.

Fig. 11 shows the test diagram. The winding configuration can be changed between the parallel and serial connections by turning the three ac switches on and off. Fig. 12 shows the test waveform. The waveform shows the inverter output current in a transient from serial mode (A-B-C-D) to parallel (E-F-G). The ac switches change the configuration of the windings between points D and E. The inverter current ramp-up/ramp-down time during the transient is about 2.45ms (1.75ms from C to D and 0.7ms from E to F). The total transient is only 5.0ms. Because the serial winding configuration has a higher inductance, it takes a longer time to ramp up/ramp down the current than it does in parallel mode. A dc bus voltage of 100V was used in the test. Note that the current ramp-up/ramp-down time will be much faster with typical hybrid bus voltages in the range of 300–700Vdc. The test results show the designed ac switch PCB assembly can change the motor windings configuration in a short time. Research continues to be done to further reduce the transient.

V. Conclutions

In this paper, we proposed a reconfigurable windings design with fewer solid state switches. It does not have a battery short-

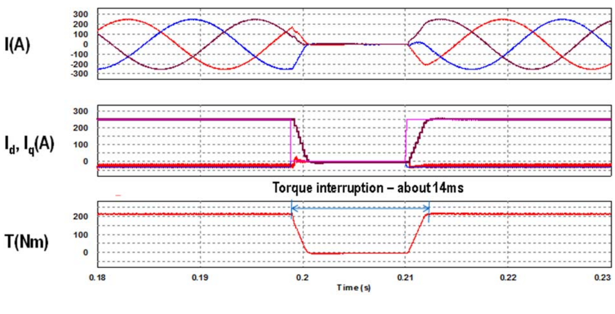

Fig. 9. Winding re-configuration dynamic of an electric drive system.

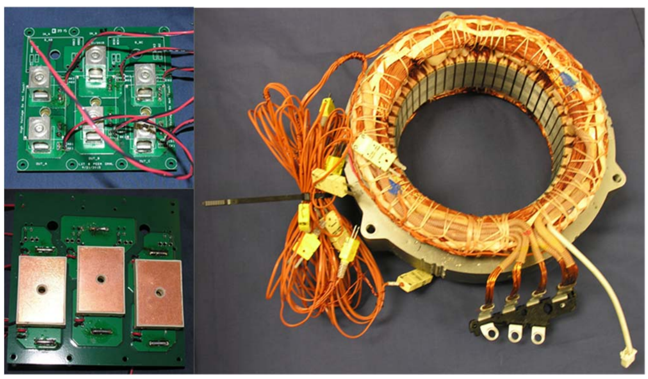

Fig. 10. Switch-box PCB and three phase motor stator used in the test.

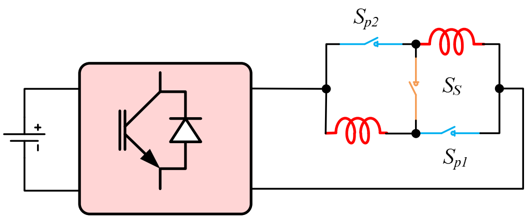

Fig. 11. Circuit diagram of the serial/parallel winding change over.

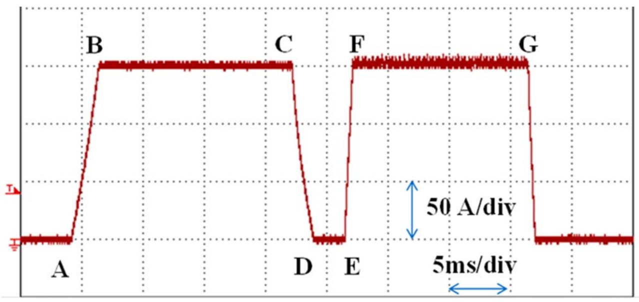

Fig. 12. Winding current during a serial(ABCD) to parallel(EFG) configuration change over, current 50A/div, time 5ms /div.

circuit failure mode. It achieves significant inverter loss reduction compared with a fixed winding motor drive and a state-of-the-art approach. A 107mm by 109mm ac switch PCB based on anti-parallel thyristors modules was designed, fabricated, and tested to demonstrate that acceptable switching times can be achieved. Initial test results show that reconfiguration can be achieved in about 5ms. Future work will include a cost study with consideration of reduced motor size, additional component and material cost, as well as comparisons with mechanical gearboxes.

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