Fabrication and Operation of PMSG

3.1 Introduction

In Chapter 2, after comparing a conventional dual stator with the novel magnetically coupled dual stator PMSG, it has been established that the Novel Magnetically Coupled Dual Stator-PMSG is better than that of conventional Dual stator PMSG. Using the proposed improved magnetic circuit model (IMC) in terms of material properties and machine dimensions, design optimizations of SSFP-PMSG and MCDSFP-PMSG has been done. It is also observed that dimension of permanent magnet, core material, rotor sleeve material directly affects the performance like generated voltage and cogging torque etc. It was also highlighted that for the low-speed machine, metal rotor sleeve are still advantageous because of low cost, better thermal characteristic and easy installation. Every combination of slot and pole cannot give balanced winding and its feasibility depends on phase offset. It was also observed that the segmented rotor limits the leakage flux and enhances the performance. So the selection of the design should be done carefully. The proposed IMC was used to predict the performance of generator as a function of dimensional parameters, core and sleeve materials in very less time compared to FEM. A prototype was developed for the experimental verification.

In this Chapter, the development of prototype, operations and fabrication difficulties have been discussed. Section 3.2 describes the development of prototype of SSFP-PMSG which deals with all the components of the proposed generator and challenges in developing the magnetic poles. Section 3.3 deal with the electromagnetic performance of SSFP-PMSG and Section 3.4 covers the development of MCDSFP-

PMSG. In Section 3.5 the electromagnetic performance of MCDSFP-PMSG has been shown. The chapter is concluded in Section 3.6.

3.2 Development of Prototype of SSFP-PMSG

The detail specifications of 3.878 KVA, SSFP-PMSG has been given in Table 2.7. The generator consists of stator and rotor. The stator is having 60 slots made with 0.5 mm thick steel alloy laminations as shown in Fig. 3.1. It is fitted with a mechanical air-gap adjustable system which helps to fine adjust the airgap in the generator.

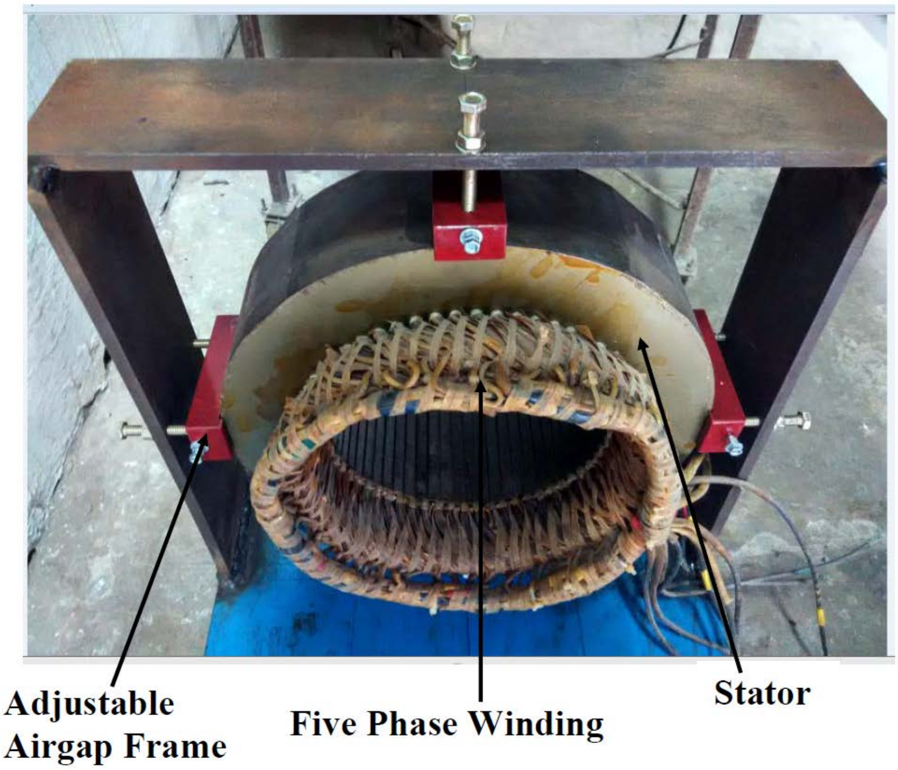

Fig. 3.1 View of stator and frame

The rotor surface of SSFP-PMSG consists of 8 poles. The poles are made of 40 small pieces of grade NdFeB magnets with dimension 6.35 mm X 6.35 mm X 2.54 mm. There are 150 pieces required for forming a complete one poles. For pasting these small magnets "mxBon" adhesive is used to hold the magnet pieces near by with same polarity (N-N or S-S). A brass frame with screws is made as shown in Fig. 3.2 to hold the magnets in place while bonding. To avoid intra-magnetic pull a rotor sleeve is used. A porous aluminum sleeve of thickness 0.46 mm is used for this purpose. There are 160 holes of 1 mm diameter present in the porous rotor PM sleeve. The eddy current loss is directly proportional to the dimensional parameters (height and effective area), whereas stress is inversely proportional to the area of sleeve.

Fig. 3.2. Rotor magnet pasting arrangement of SSFP-PMSG

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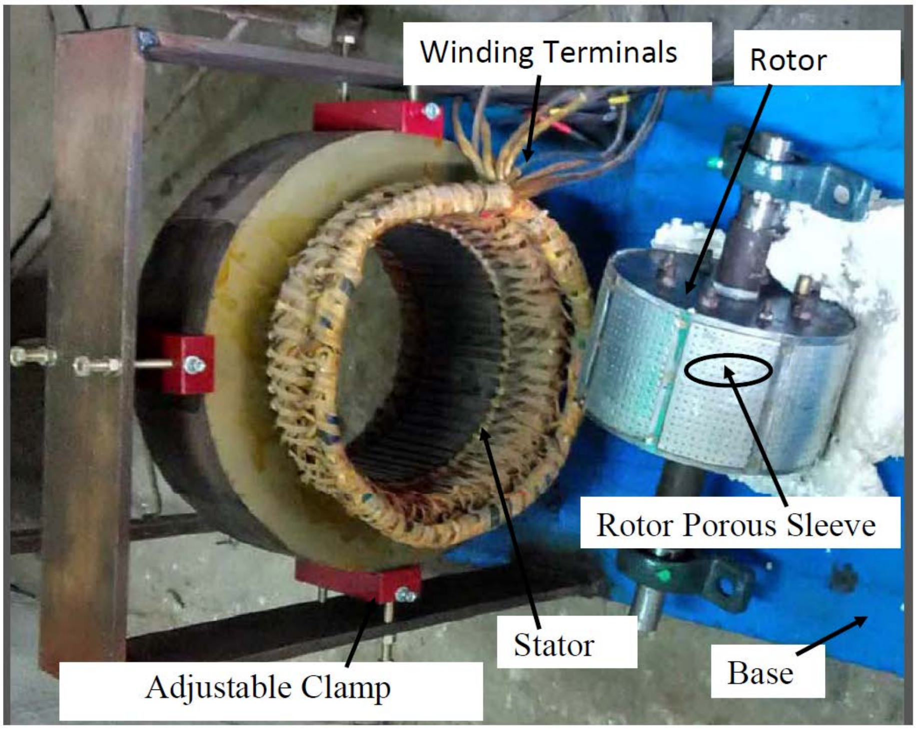

Fig. 3.3 Stator and rotor of generator

Porous sleeve limits the generation of eddy current loss to 47.16% whereas stress developed is 43.7% more compared to conventional sleeve. The porous rotor sleeve has no effect on the no-load electromagnetic performances i.e., the generated voltage and cogging torque. A sufficient air-gap length of 2 mm is provided for the protection of magnet against armature reaction during the short circuit condition of winding. The experimental setup for observing the variation of magnitude of flux density as a function of air-gap is shown in Fig. 3.3. For testing the polarity of magnets, digital gauss meter (model no.: DGM-102) is used which indicate North pole by showing the magnitude of B-field in gauss and for south pole, the B-field has Negative sign. The complete rotor and stator arrangement on the generator iron bed are shown in Fig. 3.5. The bed is made with a mild steel sheet of 2.5 mm thickness and is fitted with two handles for carrying the generator.

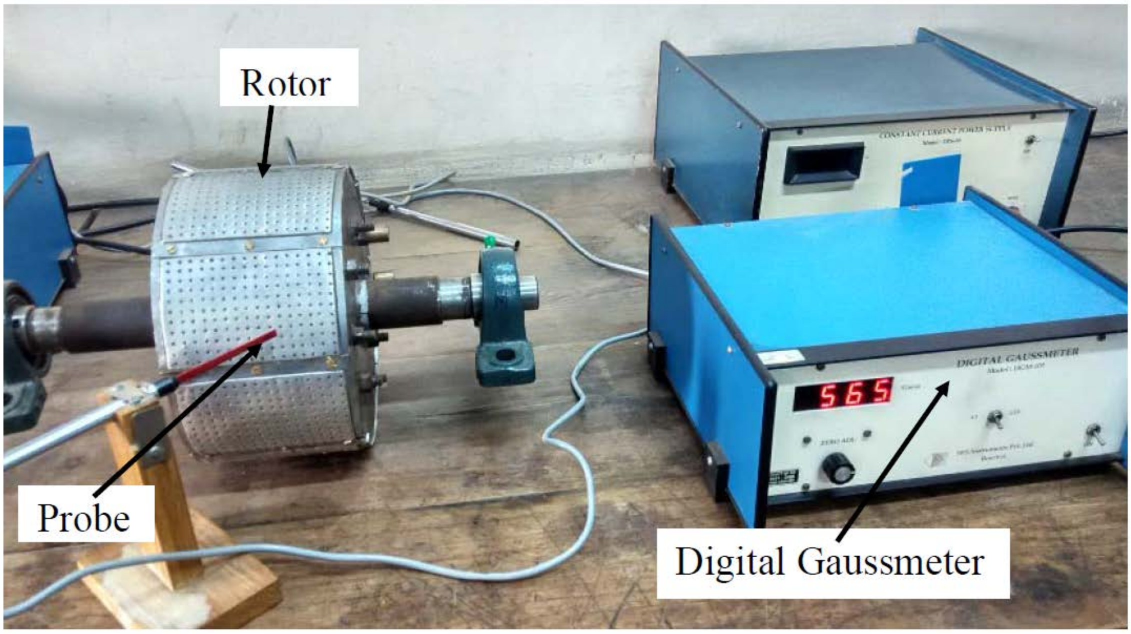

Fig. 3.4 Polarity test of rotor for generator

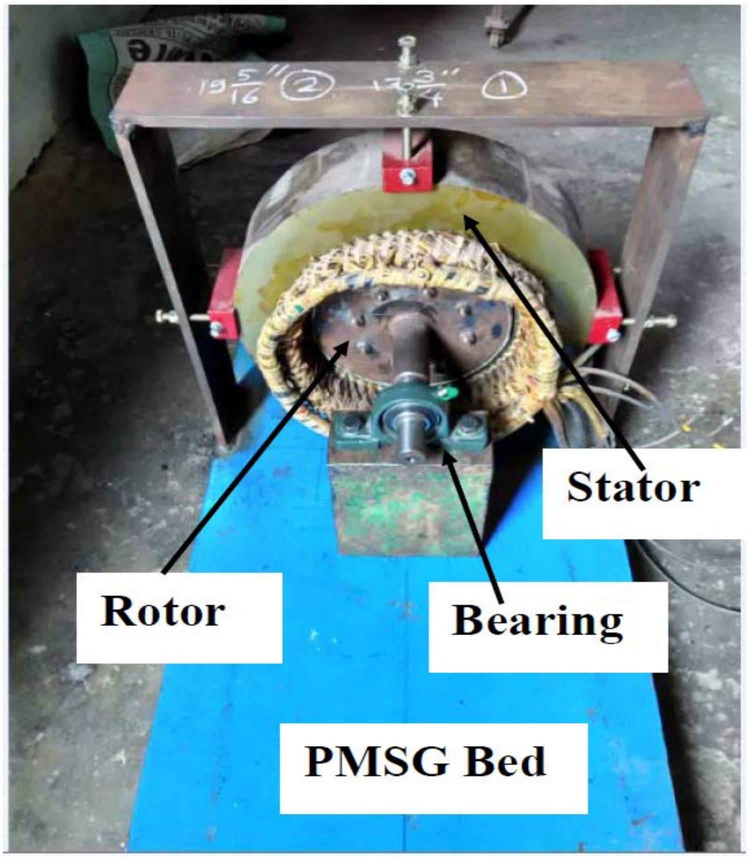

Fig. 3.5 Stator and rotor arrangement on the iron bed of the PMSG

3.3 Experimental Setup of SSFP-PMSG

The experimental test-rig of a fabricated prototype for SSFP-PMSG is shown in Fig. 3.6. The main components of this set-up are namely 3-phase supply, auto-transformer, prime-mover, five-phase PMSG, Cathode Ray oscilloscope (CRO), electrical load, current probes, and voltage probes. The generator is tested for no-load and load characteristic of SSFP-PMSG under healthy and faulty (Open circuit of phases) conditions.

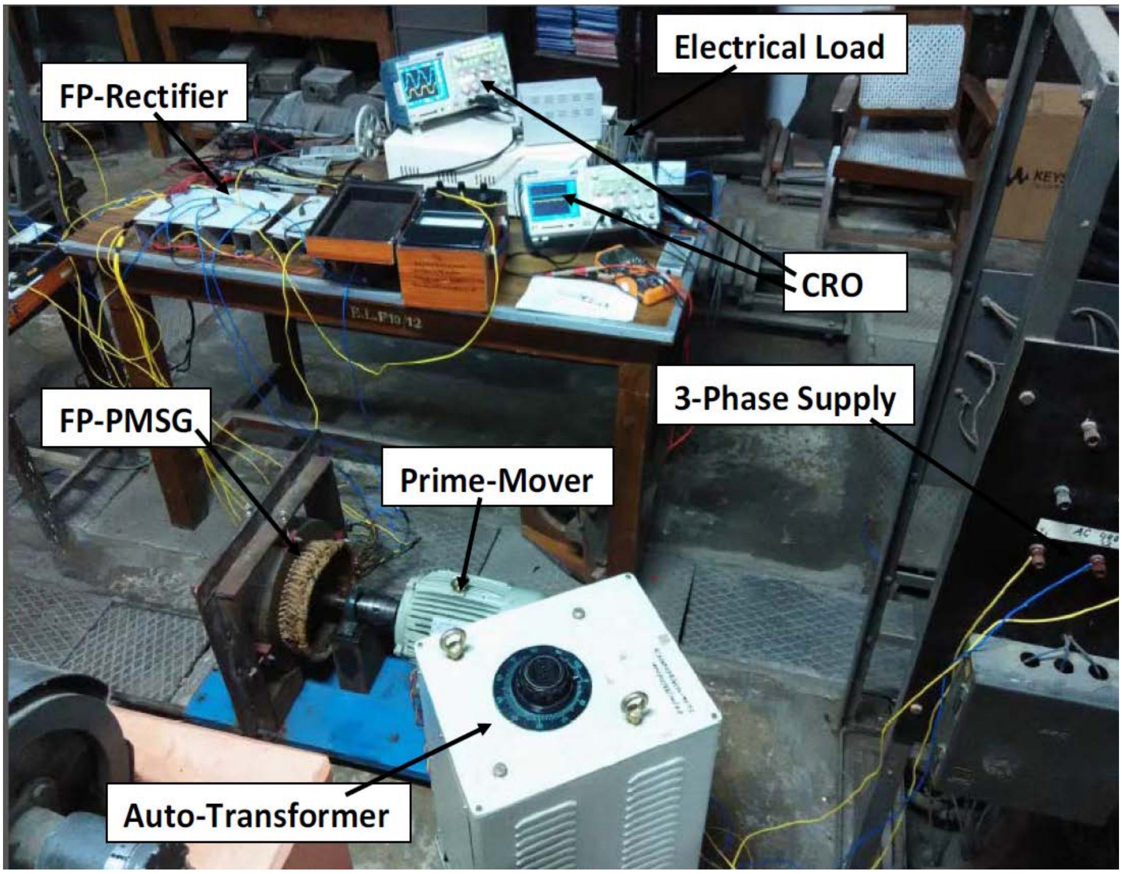

Fig. 3.6 Experimental Setup

3.3.1 Electromagnetic Performance Testing of SSFP-PMSG

It is found that at 384.59 RPM the generated voltage is186.45 volts at 25.64 Hz and the rectified DC voltage is 373 volts shown in Fig. 3.7. The generated five-phase voltage at the rated speed 400 RPM is 193.92 volts and are separated to each other by 72^{o} as shown in Fig. 3.8.

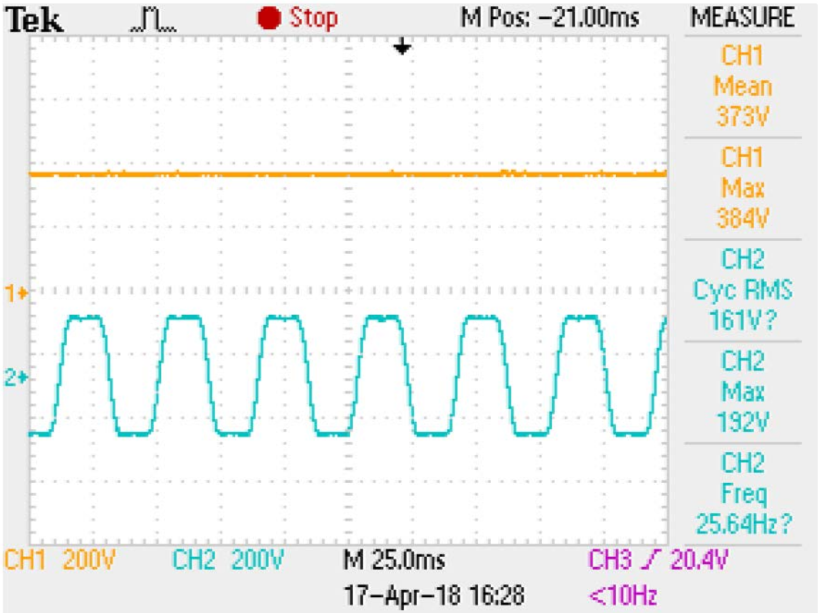

Fig. 3.7 Voltage develop at 384.59 RPM

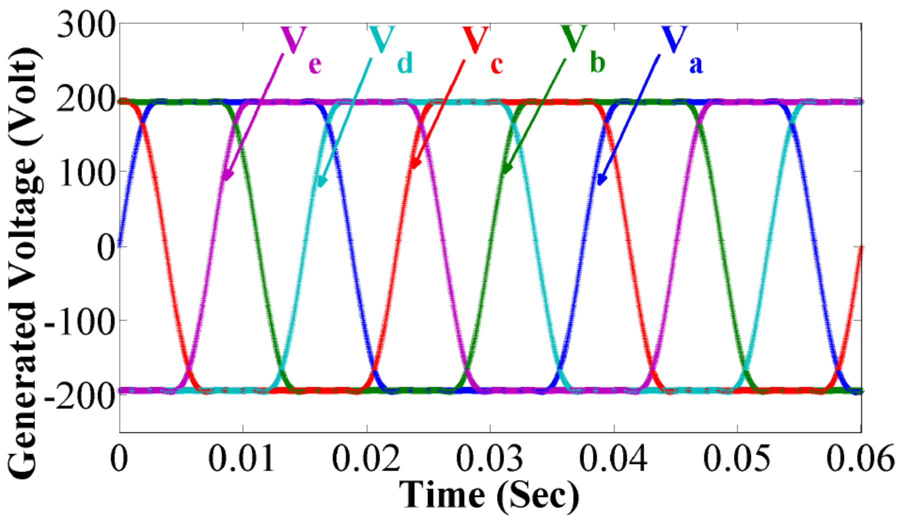

Fig. 3.8 Five-Phase generated voltages

The no-load generated voltage is found to be in a linear relationship with speed as shown in Fig.3.9. As the speed varying between 100 RPM to 400 RPM, the generated voltage varies from 48 Volts to 193.94 Volts. Corresponding to the phase voltage the rectified DC voltage also increases with the increase in speed linearly.

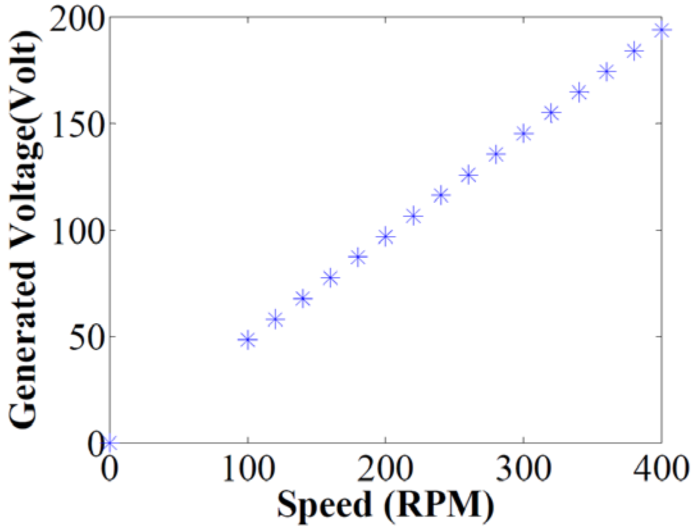

Fig. 3.9 No-Load Generated phase Voltage vs. Speed

This relationship can also be obtained under different open circuit fault conditions including B Phase open, C Phase open, B&D phases open and B&C phases open, which is shown in Fig.3.10. At 400 RPM the DC Voltage is found 0.898 % lesser in value for C phase fault, 1.823% lesser value for B phase open circuit fault, 2.528% lesser in value for B&D fault and 20.295% lesser in value for B&C phase open circuit fault in comparison with healthy conditions 386 Volts DC rectified voltage respectively.

The loading of the SSFP-PMSG is performed using five phase diode rectifier at DC current of 10A, rectified DC voltage is found to be 18.134% lesser than the no-load voltage at the rated speed. The drop in voltage is due to the generator parameters and diode forward voltage drop. Fig. 3.11 shows the same relationship under different open circuit fault scenario. At 10A of DC current, as compared to healthy conditions, the DC voltage is reduced by 2.531% when C phase is at open circuit fault and by 3.164%

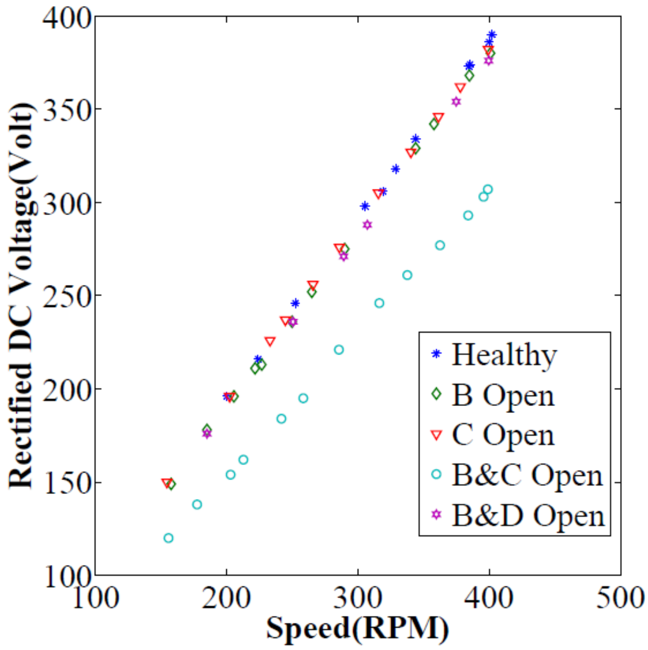

Fig. 3.10 No-Load Generated Voltage vs. Speed under open circuit Fault

The loading of the SSFP-PMSG is performed using five phase diode rectifier at DC current of 10A, rectified DC voltage is found to be 18.134% lesser than the no-load voltage at the rated speed. The drop in voltage is due to the generator parameters and diode forward voltage drop. Fig. 3.11 shows the same relationship under different open circuit fault scenario. At 10A of DC current, as compared to healthy conditions, the DC voltage is reduced by 2.531% when C phase is at open circuit fault and by 3.164% when B phase is at fault. Additionally, a decrement of 3.481% and 25.949% is observed with respect to healthy DC voltage when phases B, D and B, C are under open circuit fault respectively.

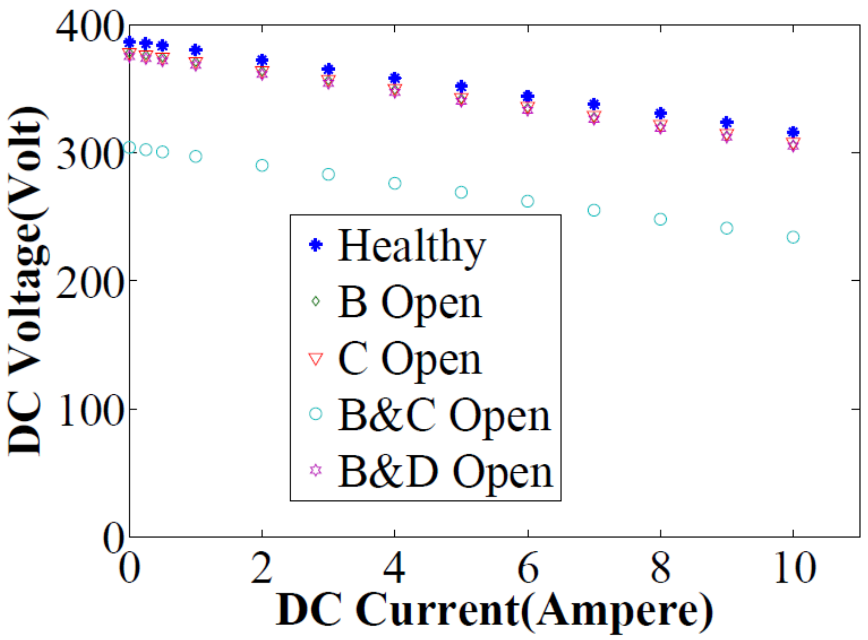

Fig. 3.11 DC Voltage vs. Current under different condition

3.4 Development of Prototype of MCDSFP-PMSG

The detail specifications of 5.12 KVA, MCDSFP- PMSG have been discussed in Table 2.8. The generator consists of two stators and one segmented rotor. There are 20 slots on outer periphery of inner stator and 60 slots on the inner periphery of outer stator as shown in Fig. 3.12 and Fig. 3.13 respectively. There are two sets of five-phase double layer winding present on both of the stators. Fig. 3.14 shows the 20 coils used for the inner stator winding. The coil has 28 turns of copper wire of 19 standard wire gauge (SWG) having 160 grams weight. Fig. 3.15 shows the coil placement in the slots of inner stator core. Similarly, 60 coils are placed in the slots of outer stator. The coils are shown in Fig. 3.16. One coil contains 36 turns with coil span of 168^{o}E or 7 slots. Fig. 3.17 shows the complete connection of all coils in the outer stator winding. Since the inner stator winding is inside the rotor so it can come out only from the shaft of the generator as shown in Fig. 3.18.

Fig. 3.12 Outer stator

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Fig. 3.13 Inner stator

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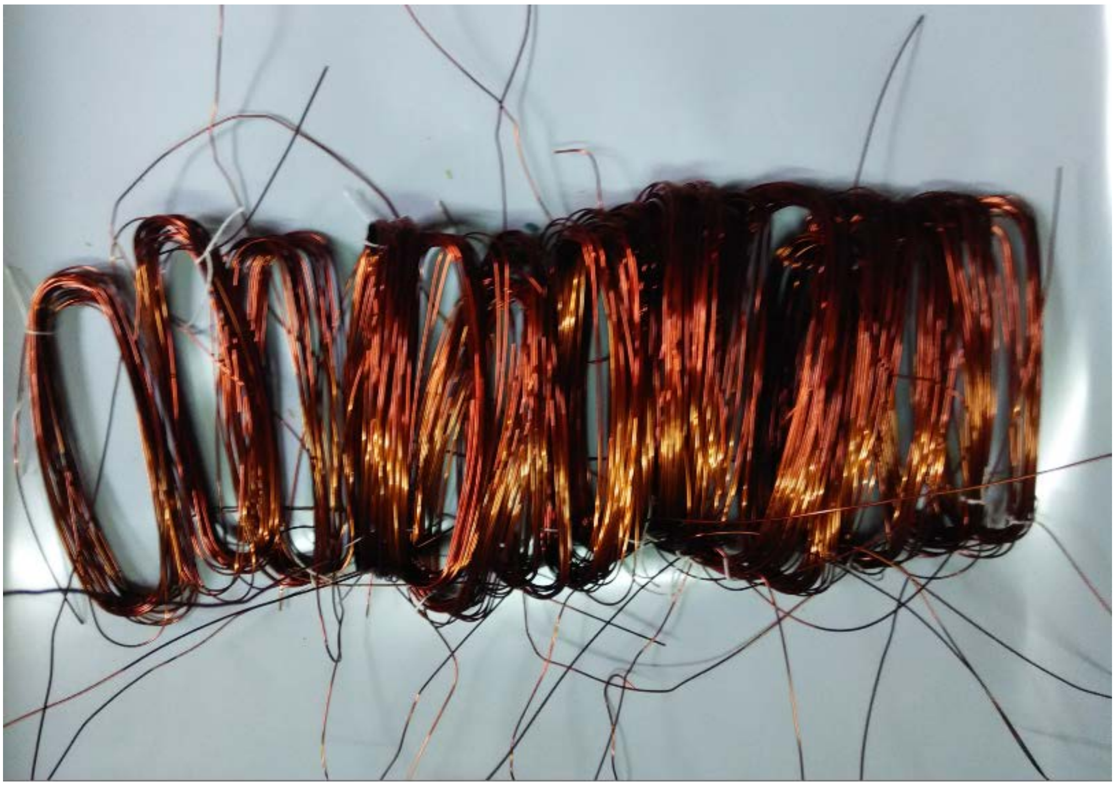

Fig. 3.14 Coils of inner stator winding

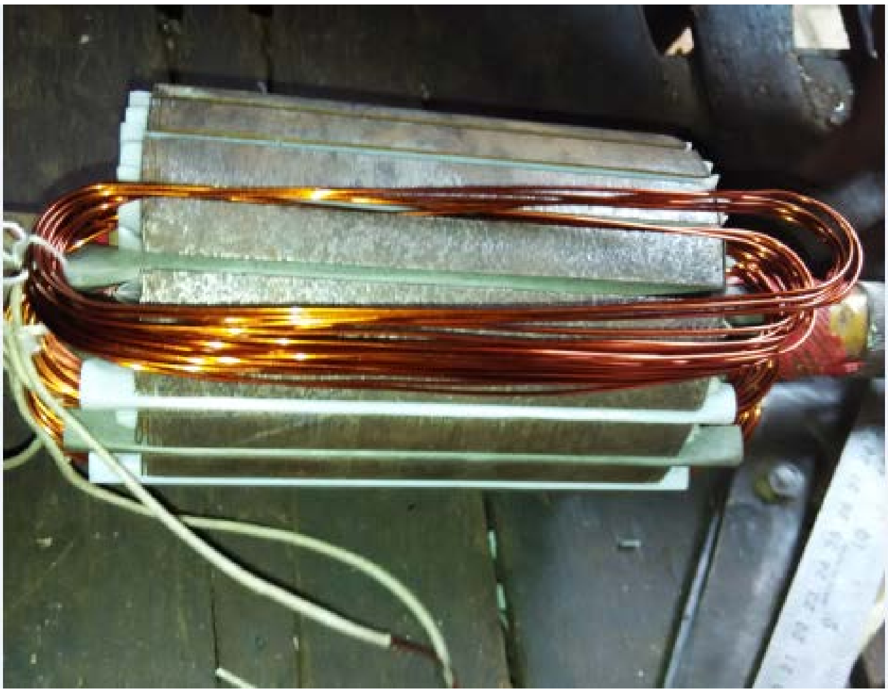

Fig. 3.15 Coil placement in the slots of inner stator

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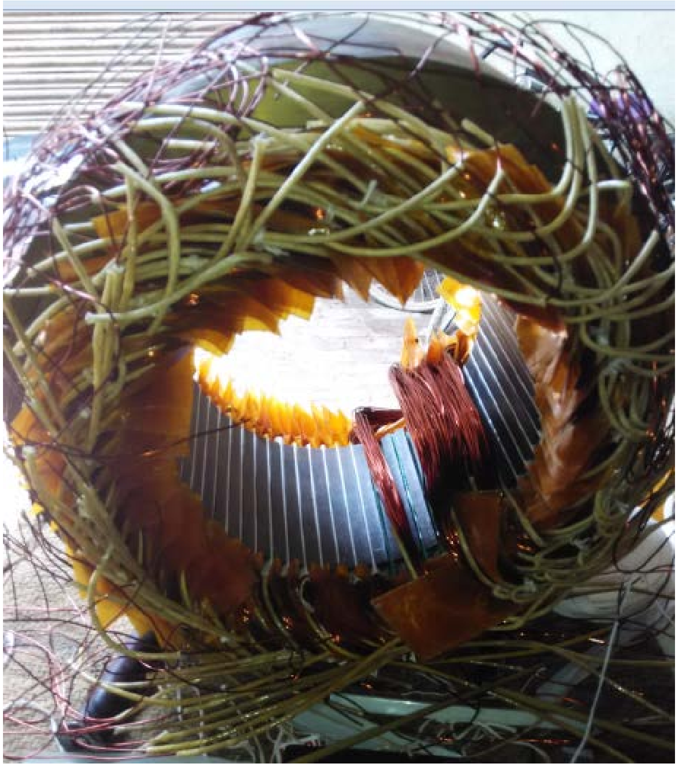

Fig. 3.16 Coil placement in the slots of outer stator

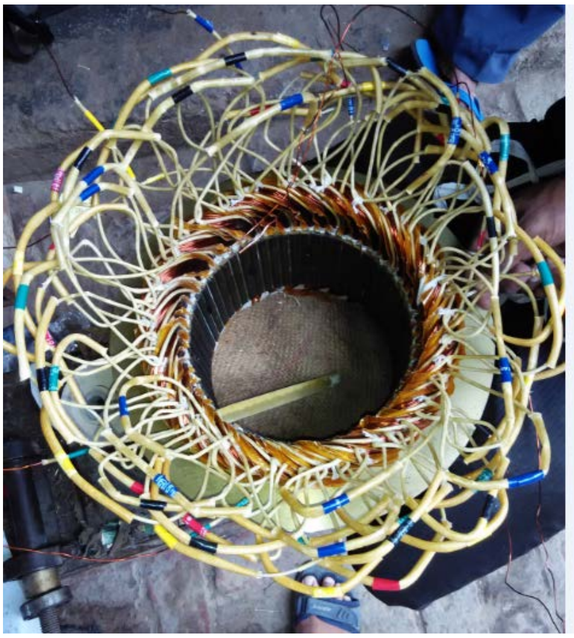

Fig. 3.17 Complete winding connection of outer stator winding

Fig. 3.18 The winding of inner stator coming through the shaft of the generator

For the magnetic coupling of the rotor, it is segmented into eight parts, where all segments are separated by 4 degrees mechanical. The segmented rotor has permanent magnets on both the surfaces of rotor segments. Rotor poles are covered with rotor sleeve as shown in Fig. 3.19. All main components of the MCDSFP-PMSG are shown in Fig. 3.20.

Fig. 3.19 Porous Rotor PM sleeve

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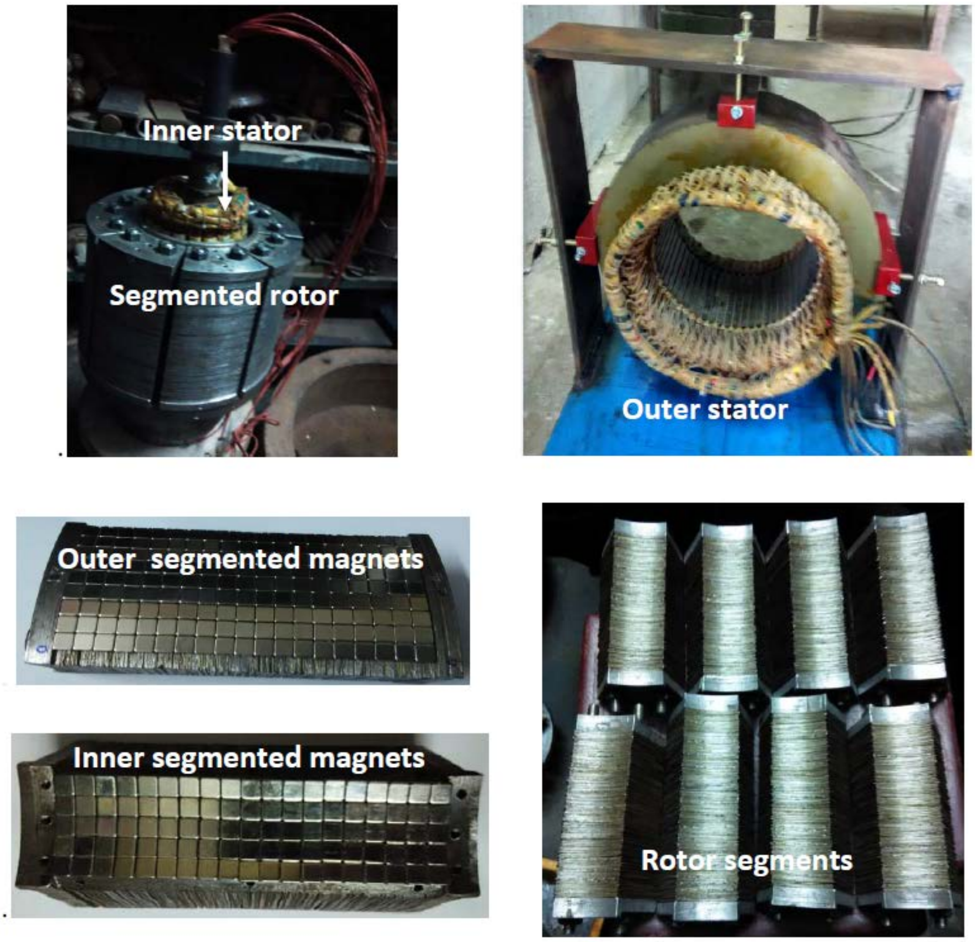

Fig. 3.20 Components of fabricated MCDSFP-PMSG

3.5 Test Rig of Prototype of MCDSFP-PMSG

The experimental test-rig of the fabricated prototype for MCDSFP-PMSG is shown in Fig. 3.21. The main components of this setup are namely 3-phase power supply, auto-transformer, prime-mover, PMSG, Cathode ray oscilloscope (CRO), electrical load, five-phase diode rectifier, current probes, and voltage probes. The generator is tested for no-load and load characteristic of MCDSFP-PMSG under healthy and faulty conditions.

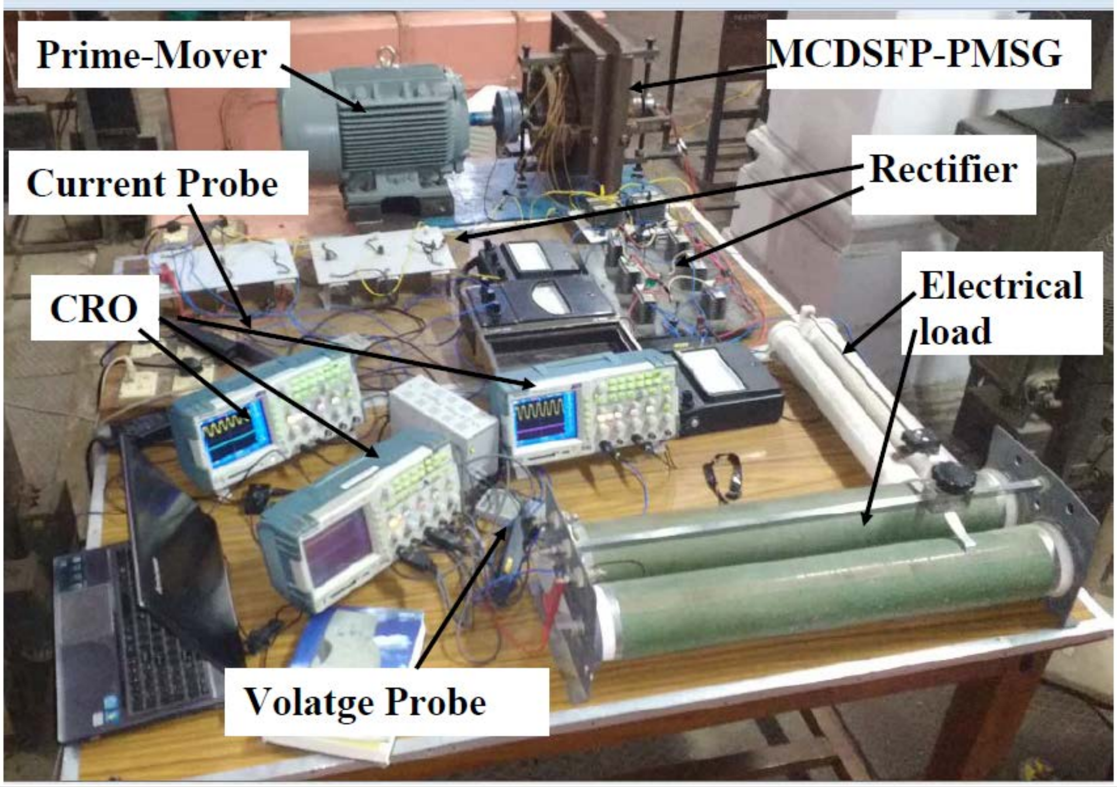

Fig. 3.21 Experimental Setup

3.5.1 Electromagnetic Performance Testing of MCDSFP-PMSG

It is found that at 400 RPM the generated phase voltage from outer stator winding is 224 Volts at 26.67 Hz and the rectified DC voltage is 425Volts as shown in Fig. 3.22. Similarly, at the rated speed the generated phase voltage from inner stator winding is 32 Volts at 26.67 Hz whereas the rectified voltage is 67.8 volts as shown in Fig. 3.23. To know the generator characteristic it can be loaded in three ways namely (a) when outer stator is loaded and inner phase is kept open, (b) when inner stator is loaded and (c) outer stator phase is kept open and both the stator winding are loaded simultaneously. For loading both the stator simultaneously the two sets of diode rectifier of five phases are connected to the generated voltage of inner and outer winding. The rectified DC voltage of the outer and inner stator voltage varies with the DC load current as shown in Fig. 3.24 and Fig. 3.25 respectively are found drooping in nature due to the dropping in the phase voltage which are dependent on the generator parameters like phase resistance, inductance and armature reaction.

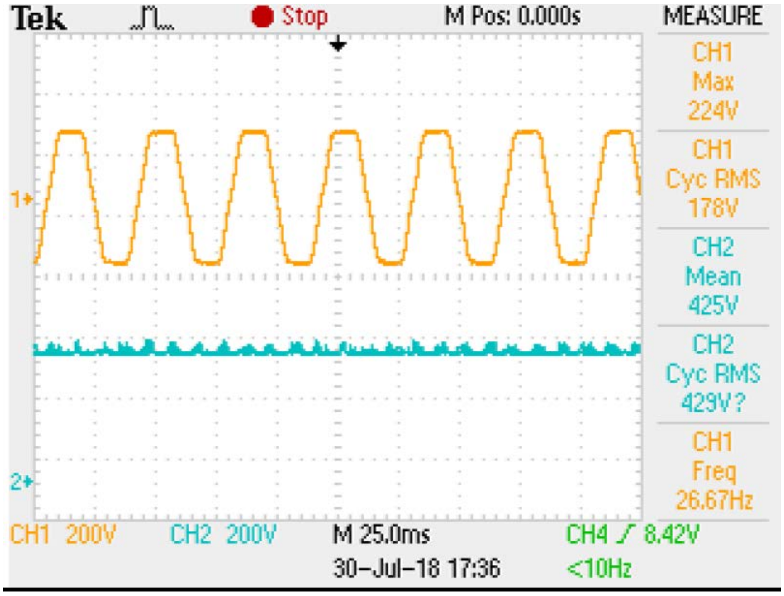

Fig. 3.22 Outer stator voltage developed at 400 RPM

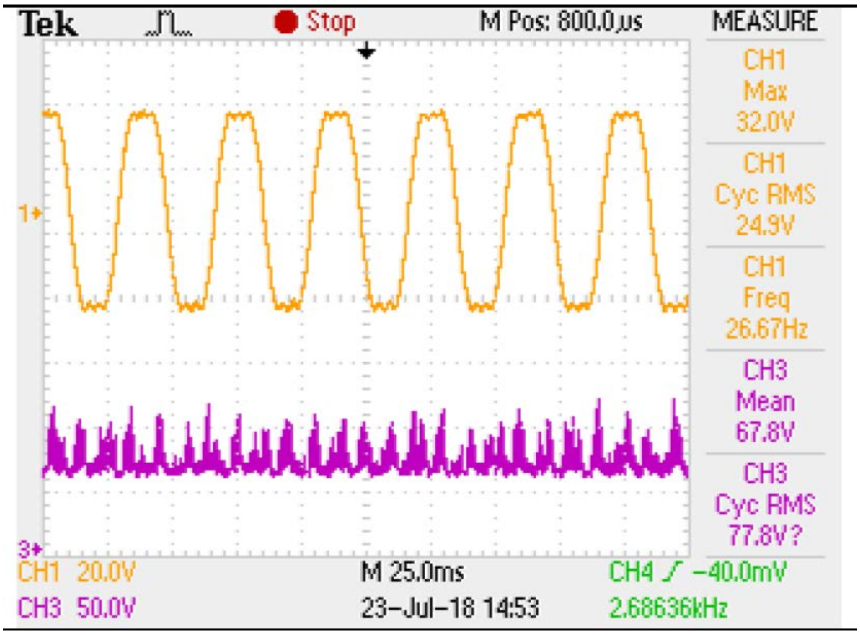

Fig. 3.23 Inner stator voltage developed at 400 RPM

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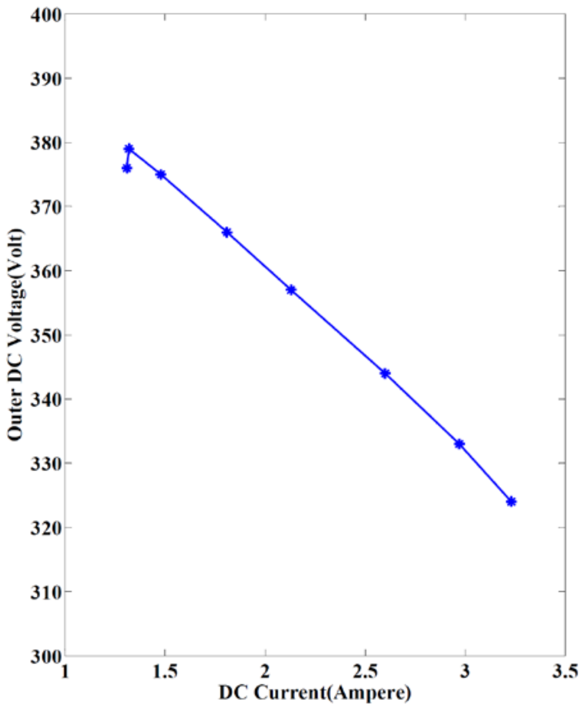

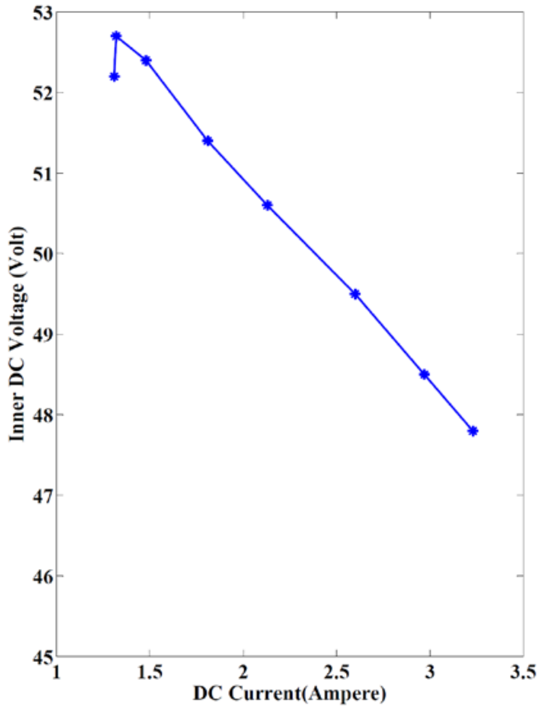

Fig. 3.24 Outer stator voltage

Fig. 3.25 Inner stator voltage

Having two sets five phase windings (inner and outer) there are several types of connections possible by connecting both the winding either in series or in anti-series. The possible series connections of winding possible are, A-A-’a-a’, A-A-’b-b’ and A-A-’c-c’. Fig. 3.26 shows the series connections of A-A-’a-a’ with two sets of windings. Fig. 3.27 shows both the series connected winding the resultant phase and rectified DC voltages. The magnitude of resultant DC voltage in this case is 495 volts which is higher than the both the stator voltages. So by using these connections a higher voltage can be achieved. Fig. 3.26 show the resultant voltage of series connections all three like A-A’-a-a’, A-A’-b-b’ and A-A’-c-c’ with speed and is found that the resultant voltage of A-A’-b-b’ is higher than the A-A’-c-c’ connection. It also shows the least resultant voltage was found in A-A’-a-a’ connection because of the special phase shift between inner and outer stator winding arrangement.

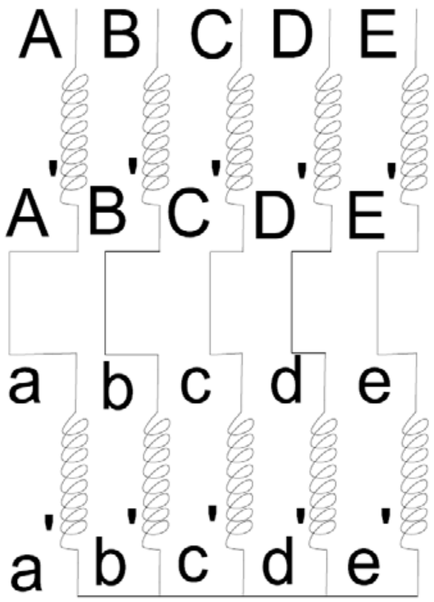

Fig. 3.26 Series Connection

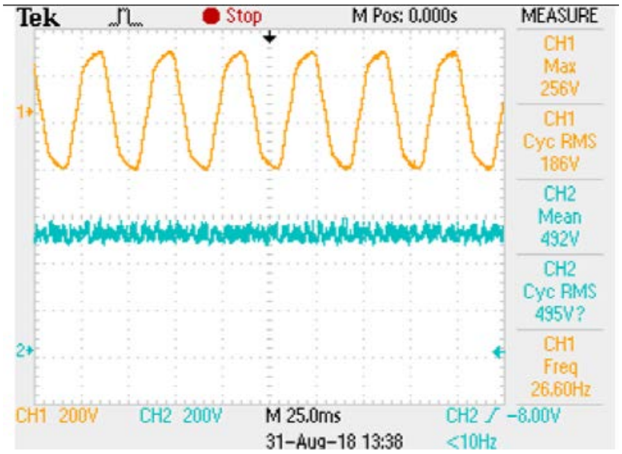

Fig. 3.27 Resultant phase and rectified DC voltage due to series connection of winding

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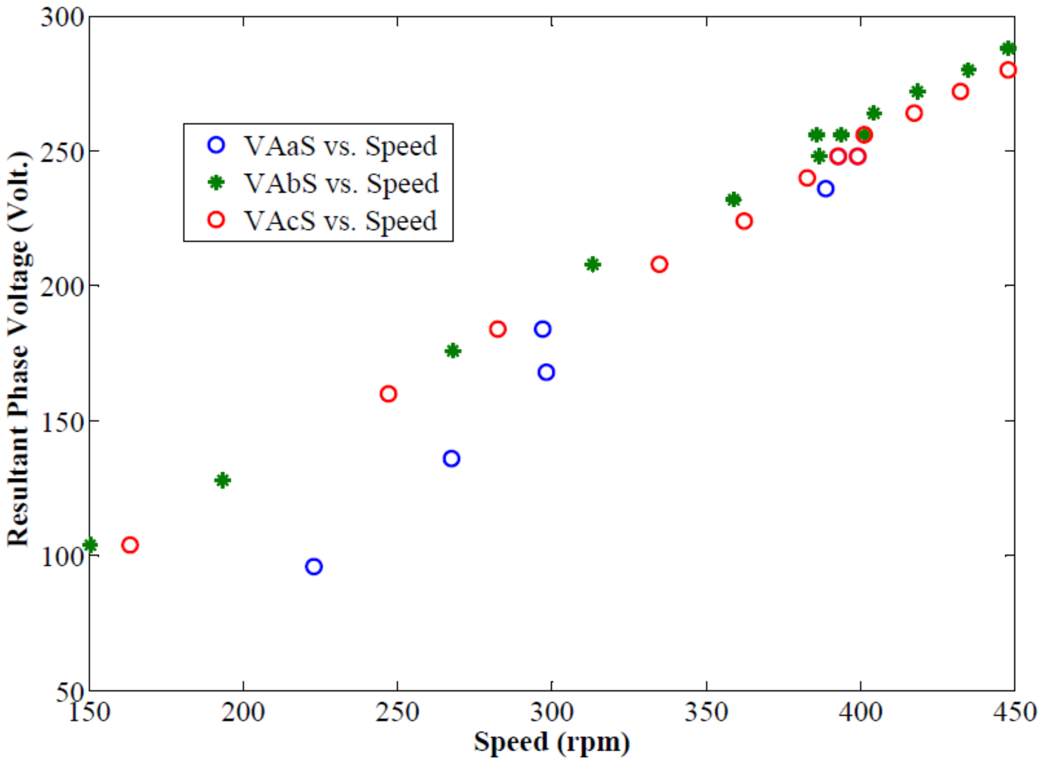


Fig. 3.28 Resultant voltage vs. speed when both are in series connection under no-load

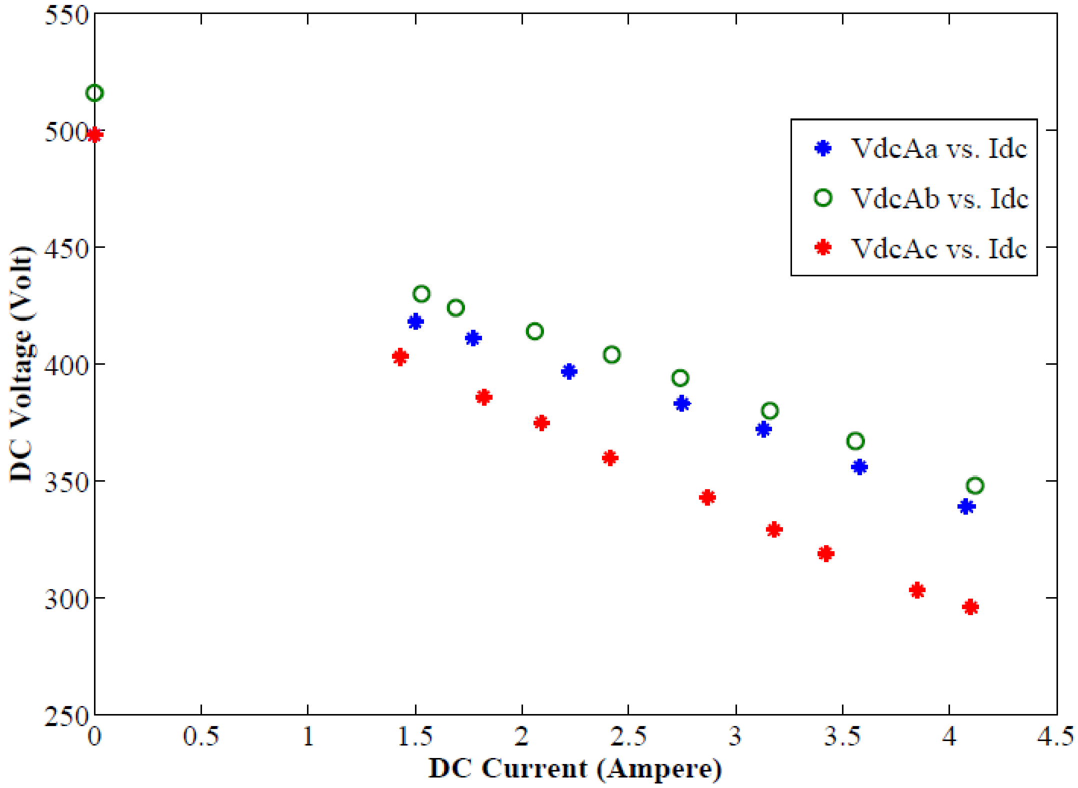
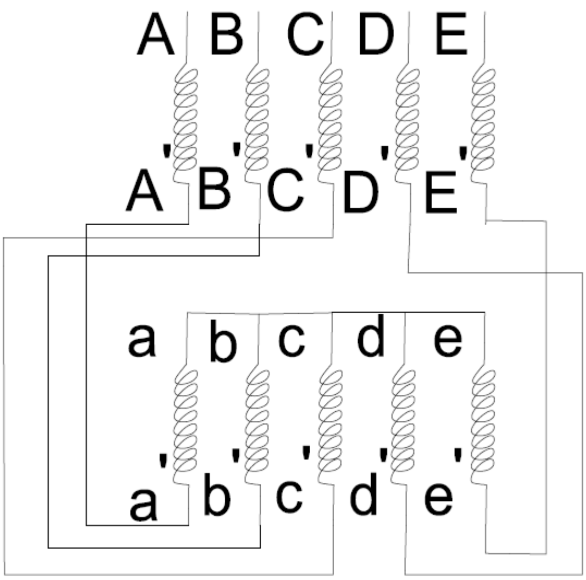


Fig. 3.29 When both are connected series the resultant DC voltage vs. DC current under loaded condition

The series connected sets of windings are loaded and drooping characteristics is found, which is similar to the phase winding under loading condition as shown in the Fig. 3.29.

There are other possibilities with two sets of winding in anti-series connection the possible connection are A-A’a’-a, A-A’-b’-b and A-A’-c’-c connection as shown in Fig.3.30. Effectively the resultant voltage of the anti-series connection of winding is reducing as shown in Fig. 3.31. The generated voltage of anti-series winding with all possible connection like A-A’a’-a, A-A’-b’-b and A-A’-c’-c connection are found to be in linear relationship with speed as shown in Fig. 3.32.



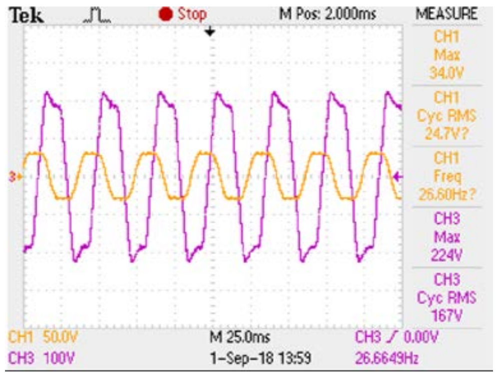


Fig. 3.31 Resultant phase and inner phase voltage due to Anti-series connection of winding

Fig. 3.30 Anti-Series Connection

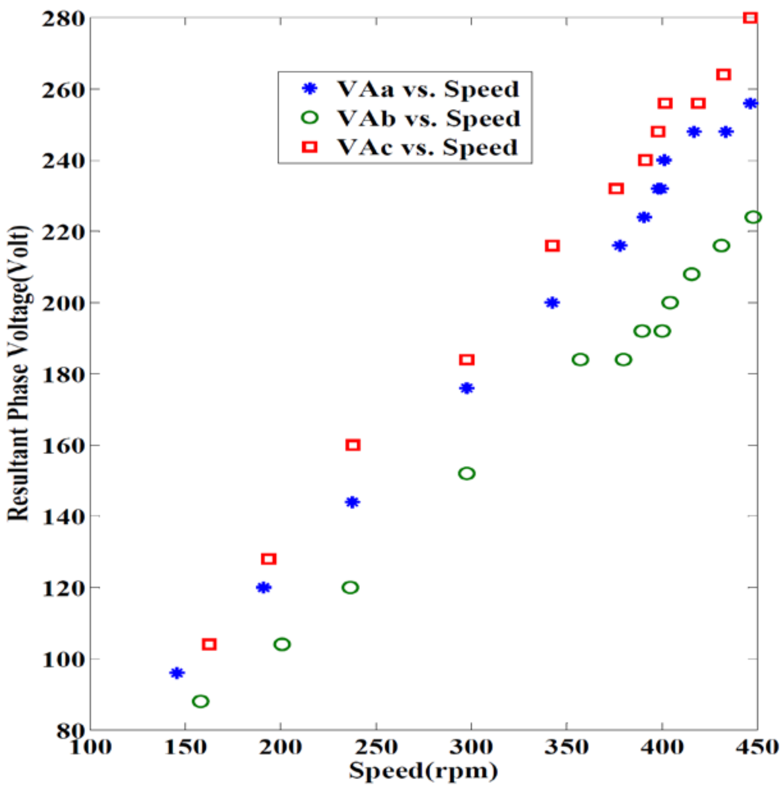


Fig 3.32 Resultant voltage vs. speed under no-load condition, when both are connected in anti-series.

3.6 Conclusion

The main issues faced during the fabrication and development of the prototypes of both SSFP-PMSG and MCDSFP-PMSG have been mentioned. The double layer fractional slot five phase stator windings is not conventional, so its winding connections are not easily available and thus needs extra care during development. The pasting of small pieces of same polarity of magnets to form a complete pole is quite cumbersome and for this purpose a non-magnetic frame is needed to be acquired. To hold the magnets, rotor sleeve of low cost has been proposed which ensures the strength of magnetic poles. The segmented rotor enhances the magnetic coupling of flux between inner and outer PMs.

The electromagnetic characteristic of both the SSFP-PMSG and MCDSFP-PMSG are covered under no-load and loaded conditions. The nature of generated voltages is found linear to be in relationship with the speed. The loading characteristic of PMSG can easily be found out with the use of diode rectifiers. The double sets of winding can provide different voltage levels with different connection like series and anti-series connections.

With the help of MCDSFP-PMSM, it is possible to regulate the DC grid Voltage in the event of speed and load variations by series/anti-series connections of different phase windings outer and inner stator.

Further the results of analytical analysis of voltages are validated by experimental results, which are covered in the result and validation Chapter.