Design, Development and Testing of 3-phase Permanent Magnet Machines and their Converters

Funding Agency	DeitY, under NaMPET-II initiatives.
Sanctioned Amount	Rs. 103 Lakhs
Project Duration	4 Years
Project Status	Recently Completed

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Brief Description of the Project

This research work has been taken up with a view to develop an indigenous knowledge base for permanent magnet synchronous machines (both motor and generator). These machines are also not commercially available from Indian manufacturers. To add to this problem, permanent magnets having high energy densities are also not available indigenously. For the present work magnets have been procured at very high costs from foreign sources. In that sense this work may be of value both academic researchers and industrial engineers.

1. The development of 5kW **PMSM** has been taken up to use it for pump type application.
2. The development of 2kVA **PMSG**has been taken up to use it as pico-hydel generators.
3. The development of 0.75hp **BLDC**has been taken up to use it for centrifugal fan type application.

The present work provides detailed guidance for electrical and mechanical design, fabrication and their constraints, converter design, implementation of different control algorithms, parameter evaluation and testing procedures of PM machines. Hence this funded research has been carried out to provide an end to end solution of PM machines and their drives which are the next generation machines as pointed out by the industry and researchers all over the world. It will be worthwhile to mention here that, there are no indigenous manufacturer of PM machines and their drives in India.

Relevance of the work with state of the art:

Due to higher efficiency, power factor and maintenance free operation, permanent magnet synchronous machines are recent trends in variable speed operation either in motoring or generating mode for low and medium power levels. In the long run, high power level PMSM is projected as a key equipment for Electric Vehicle/ Hybrid Electric Vehicle application. PMSG has already found its application in large wind power plant. These machines are inherently of high torque/inertia ratio due to permanent magnet rotating field and having extremely good dynamic response which make them almost inevitable in servo application. They need position sensor mounted on the rotating shaft and a power electronic converter for speed and current control. Their biggest advantages are, hardly any maintenance and energy efficiency due to PWM technology. The challenges of PMSM technology are high cost and non-availability of magnets. Still owing to their several advantages researchers and engineers are working to reduce the cost of these machines and trying to out-compete induction motors. Also maintaining terminal unity p.f. is the other key requirement. This can be achieved with appropriate control with Power Electronic converters. With the above discussions, it can be strongly stated that this research work has deep impact on the state of the art drive technology.

PMSM: These energy efficient motors replace induction motor almost in all applications of drive technology in medium power level. Effort is being made to use these motors in higher power level. They are envisaged as key apparatus in hybrid electric vehicle market.

PMSG*:* These alternators are already in use for small wind mills, captive power plant. The machines are being planned in large wind mills without any gear box.

BLDC*:* In small and medium power level BLDC motors are being used in disc drive PCs, electric bi-cycles. Efforts are being made to use it in domestic fan application.

Keywords: Permanent Magnet, PMSM, PMSG, BLDC, Design, Fabrication & Full scale Testing FPGA based speed control technique.

Methodologies/Approaches Adopted:

The methodology used to execute the project are as follows accordingly.

1. Resource mobilization and initiation of administrative process
2. Design methodologies
3. Procurement and Vendor development
4. Fabrication of motors and converters
5. Design and implementation of Control Scheme
6. Procurement and module testing
7. Full scale testing and testing for real life applications
8. Validation and documentation

Project Highlights

A number of reputed Industrial Houses, both from private and public sectors interested in Electrical Machine Drives have visited and saw demonstrations during the last few months. Some of those are: Bharat Heavy Electrical Ltd. Tata Motors, GE Global Research Centre, Bangalore, GE motors Pvt. Ltd., HELLA –India, Kirloskar, etc.

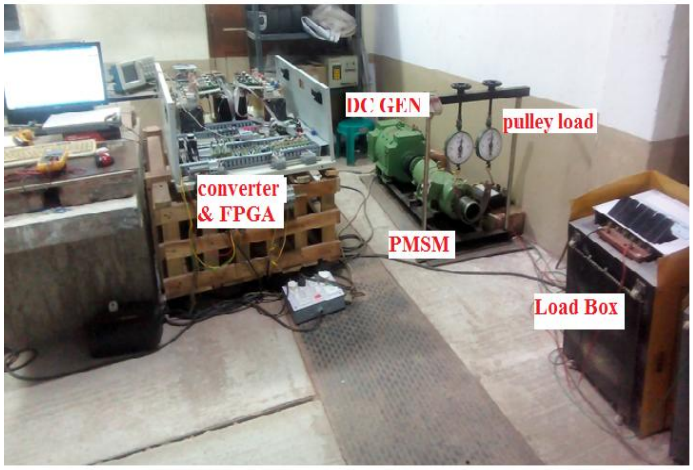
Project Achievements

Following milestones have been achieved.

A. Development of Design methodology for the following machines:

(i) *Permanent Magnet Synchronous Motor (PMSM)(5kW, 750 rpm)*

A 3-phase. 5kW, 8-pole, 250V PMSM prototype has been designed and fabricated. The PMSM design process was initiated taking the dimensions of an available existing stator lamination (of an Induction Motor of comparable power rating) as the starting point. This was done for the simple reason that this will both reduce the tooling costs and the fabrication time when the prototype machine is practically developed. This machine was fabricated with the help of a local machine manufacturer (M/S G.E. Motors, as per MoA). The design calculations were done following traditional design exercise and parameters were analytically evaluated. These parameters have also been estimated with the help of standard FEM package. The correlation between estimated and measured parameter values is found to be excellent. The design of PMSM was optimized to have minimum volume and also to protect permanent magnets from demagnetizing effect of armature current under fault conditions. The machine was tested with closed loop speed and current control techniques successfully up to 110% rated load.



5 kW PMSM- Complete test set-up

5 kW PMSM driving a pump

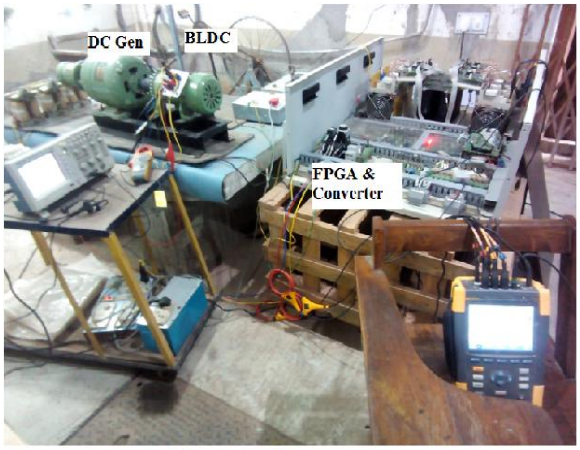
(ii) Permanent magnet synchronous generator (PMSG) (2kVA, 1000rpm)

Design, fabrication, parameter determination and testing of a 3-phase, 6 pole, 245V, 2kVA, surface mounted permanent magnet synchronous generator (PMSG) has been done for possible use in a proposed pico-hydel system. A thorough design of the machine following conventional methods was initially carried out followed by fine-tuning of the dimensions and performance parameters through repeated iterations using excel-sheet based methods backed up by design verification using a FEM-based standard software. The electrical parameters were then evaluated using analytical methods and cross-checked using the FEM model. Thereafter the machine was fabricated at the works of the above mentioned local machine manufacturer. Here also it had to go through multiple fabrication stages, particularly for the PM-rotor. A separately excited dc motor serves as the prime mover. Then the machine parameters have been experimentally determined. Finally the PMSG has been tested under load. The various stages starting from fabrication to full load testing have been developed in this project.

(iii) Brushless DC motor (BLDC) (0.75hp, 1500 rpm)

Finally, a 0.75hp (560W), 3-phase, star connected, 400 V DC-link, 1500rpm, 4-pole surface mounted PM-BLDC (SPM-BLDC) has also been developed. Here the design (both the armature circuit and the PM field) is done for a 4-pole 0.75 hp, 1500 rpm surface mounted BLDC (SPM-BLDC). First the design and the performance analysis of the machine has been done by hand calculation. The results are then fine tuned and verified using standard finite element analysis (FEM) software. Parameters of the

machine have also been calculated. The designed BLDC motor also has been fabricated. The fabricated machine was tested in the laboratory and its parameters were experimentally evaluated. The evaluated parameters are in excellent agreement with the analytically calculated values The Design of PMSM was optimized to have minimum volume and also to protect permanent magnets from demagnetizing effect of armature current under fault conditions. The demagnetising component of the armature current (d axis current) is normally considered to be zero, which points the need for having close loop current control (in 120 degree mode with hysteresis control) operation. So, the present design considers that the BLDC machine will run under current hysteresis control.



Complete test set-up of BLDC motor


Real life testing of 0.75hp BLDC motor coupled with blower-fan load .

B. Converter topologies

Back to back converters with common DC-link have been fabricated (by M/S Veeral Control, as per MoA) for the machines in (i), (ii) and iii) above, respectively. The current and voltage sensors at different stages were included in the converter. The gate driver used here provides both short circuit and over voltage protections. The converter has the pre-charging facility which enables the converter directly to be connected to grid without any intermediate stage. Control algorithm has been implemented in FPGA platform.

C. Control strategies

For applications involving (i), (ii) and (iii) above

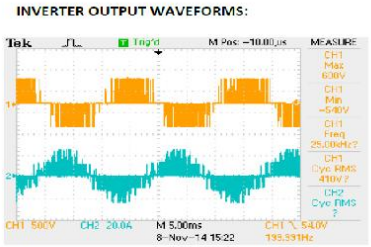
The PM machine cannot operate under open loop condition. Close loop speed control with proper speed and position sensing is required for proper operation of these machines. Also proper current control is required to protect the magnets from demagnetising due to armature ampere-turns.

Different control strategies, for appropriate speed and current control of these three machines, have already been implemented as a part of the previous project and reports has been submitted. The control strategies implemented include different popular configurations like hysteresis current control, vector control and closed loop V/f control. The details can be found in the Technical Report referred above and in the technical papers published (which have also been included in the report).

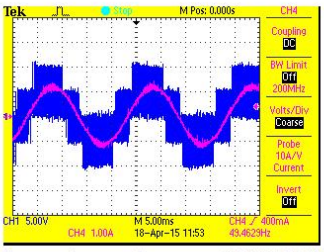
D. Hardware Set-up

1. Fabrication of one prototype each for the machines named in para A above at the mentioned power level has been done with utmost care and precision achievable for a single piece prototype.
2. Fabrication of PE Converters and running with FPGA control platform and other sensing and
3. Feed-back accessories as broadly indicated in B and C above are the other hard-ware implementation highlights.

Fabricated converter- 10 kVA, FPGA based back to back converter



Inverter voltage and current with R-L load



Phase voltage and current of 5 kW PMSM

E. Real life applications have been demonstrated, as additionally instructed by the PRC-III.

The PRC-III had in one of its later meetings recommended stringent trials of the successfully designed and fabricated drives on real life applications. Accordingly, (i) the BLDCM was chosen by the PRC- III members for application on a FD fan and (ii) the PMSM on a pump load. The machines were coupled to these loads inside the laboratory premises and tested. The same were demonstrated to the experts and PRC-III members in real running condition.

Publications :

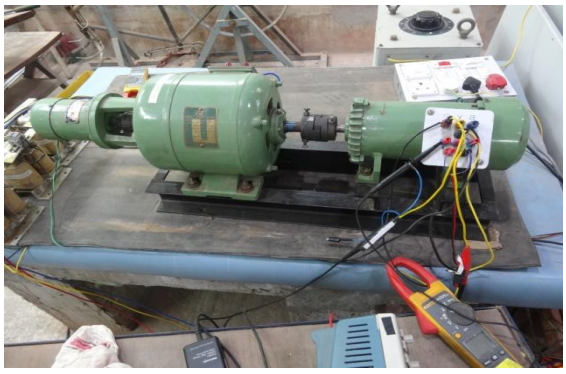
1. Nanda S, Sengupta M and Sengupta A, 'Modeling, Real-Time Simulation, Fabrication of and Experiments on a Boost-Buck (Cuk) Converter', proc. of NPEC 2013 conference.
2. Nanda S, Sengupta M and Sengupta A, 'Modeling, Simulation, Fabrication, Experiments and Real-Time Linear State Variable Feedback Control of Cuk Converter using Pole Placement Technique' Trans. of The Institution of Engineers (India): Series B , Volume 95, issue1, Jan-Mar 2014.
3. Paitandi S, Sengupta M, ' Design , Analysis of a Permanent Magnet Synchronous motor and its comparative with 3-phase induction machine of same nominal rating. ', proc. of NPEC 2013 conference.
4. Mukherjee P, Sengupta M, 'Design, Analysis and Parameter Calculation of a Brush-less DC Motor', proc. of PEDES - 2014. IEEE Conference.
5. Paitandi S, Sengupta M, 'Design, Fabrication and Parameter Evaluation of a Surface Mounted Permanent Magnet Synchronous Motor', proc. of PEDES - 2014. IEEE Conference.
6. Nanda S, Sengupta M 'Design, Analysis, Fabrication and Investigations of a Permanent Magnet Synchronous Generator for different renewable energy applications', proc of PEDES - 2014. IEEE Conference.

Facilities Developed:

A. Development of Design methodology for the following machines

(i) Permanent Magnet Synchronous Motor (5kW)

(ii) Permanent magnet alternator (2kVA)



(iii) Brushless DC motor (0.75hp)

B. Converter topologies

For the machines in (i), (ii) & (iii) above

C. Control strategies

For applications involving (i), (ii) and (iii) above

D. Hardware Set-up

Fabrication of one prototype each for the machines named in para A above at the mentioned power level.

Fabrication of PE Converters and running with FPGA control platform and other sensing and

Feed-back accessories as broadly indicated in B and C above.

E. Additionally on PRC-III member's recommendation, a real life application to be demonstrated. A fan and pump load to be coupled with the PMSM and BLDC motor and drive system to be tested.

Project Staff:

Scientific Officer: Mr. Subhrakanti Nanda pursuing PhD

Project Associate: Mr Pinaki Mukherjee pursuing PhD

Project Assistant: Mr. Sourabh Paitandi pursuing PhD

Plan of Future Project Proposal based on the Current Project

The PRC-III members and experts were unanimous in their recommendation of the need for taking these successfully developed prototypes to the TRL 5, 6 levels without much delay. Accordingly they advised the Chief Investigator of this just completed project and his team to prepare a proposal of how these prototypes can be taken to the level of a marketable commodity in stages. The plans for the same are outlined below.

1. Use of lighter and more thermally efficient shell/stator housing for the PM machines for improvement of efficiency and energy density:
2. Use of higher grade Steel in stator and rotor for improvement of energy, torque and power density:
3. Real life Testing of PMSG on pico-hydel prototype:
4. Compact, small size, dedicated power converter:
5. Design and Fabrication of Interior permanent magnet (IPM):
6. Torque ripple analysis: