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Principal Author(s): Michael J. Crowley (DR),
Prem N. Bansal (EMD),
John E. Tessaro (EMD)

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Recipient:
(Submitting Organization)
Dresser-Rand Company
P.O. Box 560
North 5th Street
Olean, NY 14760-2322

Subcontractors: Curtiss-Wright Electro-Mechanical Corporation (EMD)
1000 Cheswick Avenue
Cheswick, PA 15024

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Abstract

During this reporting period, significant progress has been made towards the development of the IEMDC System design. Considerable effort was put forth by Curtiss-Wright EMD in the resolution of the technical issue of aerodynamically induced radial forces. This has provided a design basis with which to establish the radial magnetic bearing load capacity and the rotordynamic design. Dresser-Rand has made considerable progress on the flowpath design for the compressor section particularly on the volute and inlet aerodynamic design. All efforts show progression towards the successful integration of a centrifugal compressor and variable speed electric motor ventilated by the process gas. These efforts continue to confirm the feasibility of the IEMDC system design.

Table of Contents

Introduction

This report covers the second quarter (04/01/03 to 06/30/03) of the Phase 1 of the In-Line Electric Motor Driven Compressor (IEMDC) project.

The IEMDC project is the development of an in-line electric motor driven compressor to address the needs of the Natural Gas Industry.

The objective of the first phase of the project is to develop the design of a direct coupled, seal-less, In-Line Electric Motor Driven Compressor to the point where detailed manufacturing drawings may be started. This gas compressor will be the world's first that can be installed directly in the pipeline, utilizing a variable speed induction motor with magnetic bearings that is integrated with a centrifugal compressor. It will be an electrically powered, highly flexible, efficient, low maintenance compressor that can be quickly ramped up to meet peak demands. The unit design proposes to provide low cost, low maintenance gas compression for the Natural Gas Industry while minimizing the environmental, regulatory, and maintenance issues associated with gas turbine drives by the use of an electric motor as the prime mover.

Executive Summary

Unit Configuration and Integration

The project has continued to proceed with the alternate configuration concept[1] for the integrated motor compressor. The two major technical issues identified in the first phase of the design have been an ongoing joint technical effort since the first quarter. These issues were the aerodynamically induced radial forces[2] and the interface of the two separate pressure containing cases.

The issue of aerodynamically induced radial forces continued to be an area of primary focus particularly with the electric motor subcontractor. This was identified as a technical issue of concern in the first quarter when the unit was changed to the alternate configuration. Switching to the new configuration concept required bearings with significant load capacity above that which had been specified for the original configuration. Several iterations ensued to determine the proper balance for rotordynamic performance, bearing load capacity, bearing geometry and construction, and ultimately allowable levels of aerodynamically induced radial forces.

System performance efforts required a series of iterative and detailed calculations from both DR and EMD to establish the effects of the interaction of the compressor aerodynamics and electric motor cooling circuit. Extensive compressor performance calculations were made to establish the operating envelope of the unit. Reviews of these calculations helped to select and establish possible worst case operating points. These points were used to establish the basis of operating limitations of the unit and to ensure the integrity of the design for the intended service and range of application.

Calculations for thrust balancing have also been performed to establish the effects and interactions of the electric motor cooling circuit at the edges of the compressor operating envelope. Selected points were analyzed and indicate that the thrust forces can be kept within reasonable limits. Calculation of these axial thrust forces was a joint effort between the compressor and electric motor subcontractor. Validation of the thrust balancing concept was an important step towards system integration of the IEMDC.

Compressor Design

Significant progress has been made on the design of the aerodynamic flowpath components. Four discharge system concepts have been designed using the application of one dimensional analysis techniques. Two of the concepts use volutes with an overhung design each having different tongue geometry, one concept uses a collector, and the last concept uses a constant c.g. volute design. Computational fluid dynamics analysis has been performed on the first overhung volute design and the collector design. This analysis is intended to validate the one-dimensional analysis and identify areas of the component design requiring additional attention.

During the aerodynamic review process it was determined that an alternate family of impellers should be considered for use in the compressor. This alternate family of impellers provides a better match for the operating speed envelope over the range of flow coefficients expected for use in the unit.

One-dimensional analysis techniques have also been used to design two different inlet concepts for the compressor. These inlet designs will be validated using computational fluid dynamics. The first inlet design has been undergoing evaluation and will be compared to the results of the second design as analysis efforts continue.

Electric Motor

One of the primary design challenges was to develop an acceptable limit of the aerodynamic radial load that will facilitate the completion of the mechanical design of the alternate IEMDC concept. The primary

[1] See first quarter Technical Progress Report for more details on the alternate configuration.
[2] For further reading on this subject, refer to the papers listed in the References Section.

requirement was to determine the size of the impeller end magnetic bearing to provide desired load capacity. Furthermore, the rotor-bearing design must meet the requirements of the API standards 541 and 617(7th edition) for the placement of critical speeds, rotor unbalance response, and critical speed separation margins. Therefore, the primary design effort was focused on performing several rotor dynamics analyses to determine the allowable maximum limit of the compressor aerodynamic radial load and to establish the size of the impeller end magnetic bearing capable of supporting this additional load.

New rotordynamics models of the IEMDC rotor-bearing system, with the alternate compressor design, were developed with magnetic bearings proposed by the three vendors. Initial analysis results of this considerable design effort indicated the need to reduce the aerodynamic radial load to 1,300 Lb. from the predicted max load of 2,300 Lb. If the compressor discharge system could be adjusted to the lower radial load requirements then the proposed Silicon-Iron magnetic bearings would have sufficient load capacity margin and also would have minimum impact on the cost increase. However, it was determined by DR that more design iterations should be performed by EMD to determine if the rotor system design could be further optimized in order to increase the aerodynamic radial load threshold higher than 1,300 lb.

In order to develop a viable design solution, the use of a significantly more expensive cobalt-iron magnetic bearing system was also analyzed. Thus, several more design iterations of rotordynamics analysis were performed with larger impeller side bearings. The magnetic bearing span length was adjusted to accommodate the increased bearing size by further moving the magnetic bearings under the end turns and to keep the rotor-bearing system design within the guidelines of the API standard 617. Thus, after several design iterations, and adjustments to the bearing span and bearing sizes, it was determined that the maximum acceptable compressor aerodynamic radial load was to be set at 1,600 Lb. The corresponding rotor-bearings configuration would also meet the requirements of the API standard 617. Dresser-Rand jointly established the allowable aerodynamic radial load limits with EMD and agreed that a compressor flowpath design configuration could be pursued to implement this decision.

It was further verified via FEA calculations that moving the magnetic bearings under the end turns would have no adverse effect on increasing the magnetic bearing losses by the interaction of the magnetic flux from the end turns with the flux of the magnetic bearings. This is because an effective magnetic bearing shield has been incorporated to mitigate this problem.

Detailed calculations were also performed to determine the impact of the alternate design change on motor cooling circuit design, motor cooling flow requirements, and the IEMDC thrust balancing. Dresser-Rand had proposed to EMD a total of 24 operating cases that represented the expected performance envelope. Dresser-Rand subsequently agreed with EMD's proposal to select 6-7 cases for a detailed motor cooling analysis. These cases were jointly selected as extreme operating cases with the intent of determining the range of motor cooling flow requirements. The results from this analysis were presented to DR. Also preliminary motor thrust loads and the net IEMDC thrust loads were estimated to be within the design load capacity of the proposed magnetic bearing thrust disk size. During 3rd quarter, more discussions are planned with DR to further delineate the cooling flow circuit design as well thrust balancing issues.

EMD also performed simplified analyses to size the pressurized motor housing and to evaluate the motor-compressor interface flange loading and resulting displacements. EMD is continuing to review alternate design concepts to address motor-interface design issues.

In summary, during the second quarter, EMD has made significant progress in advancing the motor design forward and has resolved major design challenges that were imposed by the alternate compressor configuration change. Thus, EMD has further confirmed the feasibility of the robust design for the 10 MW, 12,000 rpm variable speed motor.

Experimental

No experimental work was performed during this reporting period.

Results and Discussion

Unit Configuration and Integration

Performance evaluation of the integrated system continues. Each section has an effect on the performance operating characteristics of the other and complete integration requires that the resulting interactions between the electric motor and compressor be understood. The motor cooling gas circuit creates a recycle loop that affects the operation of the compressor and affects the overall compression cycle. Operating performance of the compressor creates the conditions for the discharge process gas that is used as the cooling medium for the motor ventilation circuit. An essential understanding of this interrelationship is essential to the success of the system. As the design evolves and changes are made the effect on the motor cooling circuit, motor design and potential impact on the compression cycle require continual review.

Future expectations for the project include the continued evaluation of system performance and implications on the integration of the compressor and electric motor. The issue of the interface between the two pressure containing cases was secondary to the aerodynamic radial loads issues and has only been a topic of design discussion in the latter part of the second quarter. Mechanical interface design issues will be further explored in the next quarter.

Compressor Design

Preliminary thermodynamic calculations were made of compressor operating performance. These calculations helped to establish the operating parameters and design basis of the unit of the unit including, sizing and selection of aerodynamic components, motor cooling gas conditions, and axial thrust forces.

An alternate impeller family was selected for application in the unit. The primary reason to change to this impeller family was to provide a better match for the range of flow coefficients expected over the operating range of the unit. In addition the alternate family will better accommodate the mechanical considerations of the unit including thrust balancing. The effect of the switch to the alternate impeller family on the motor design was coordinated with the electric motor subcontractor. New tables of impeller mass property data were generated and supplied to EMD for evaluation.

The casting vendor reviewed the preliminary conceptual compressor pressure containing case casting drawing and a quotation was received. It was confirmed that the case casting could be made with some concessions to assist with the casting process. Knowing that there is an option to cast permits an additional radial inlet design concept to be evaluated during the aerodynamic design process.

Compressor aerodynamic design efforts will continue into the next quarter on the new flowpath arrangement. This will include analysis efforts of the second overhung volute design and the constant c.g. volute design in the discharge system. Also the second inlet design concept is in progress. An evaluation on these different inlet and discharge component designs will determine which designs offer the best compromise between aerodynamic performance and mechanical considerations of the unit.

Electric Motor Design

EMD has continued to make significant progress towards evolving a robust and efficient design of the 10 MW 12,000 rpm variable frequency motor capable of meeting the operational goals of the IEMDC system. The predicted motor efficiency is over 94%. Due to the dedicated teamwork of the DR/EMD design team, significant design challenges such as sizing of the magnetic bearings, to meet additional requirements of the alternate design compressor aerodynamic radial load, have been resolved successfully. The results of the rotordynamics analysis are consistent with the requirements of the API standard 617, 7^{th} edition. Thus, a sound design process has been established. This would help further to expedite verification of the feasibility of the innovative IEMDC system design.

During the 2nd quarter reporting period, the primary focus was to evaluate the motor design as impacted by the compressor aerodynamically induced radial load. The predicted aerodynamic load of 2,300 Lb. caused increased bearing span because this required a larger magnetic bearing at the impeller end. Consequently it was not possible to meet the requirements of bearing load capacity as well API standard specification. The motor winding design was changed to half coil from the full coil due to the recommendations from the stator manufacturers. This allowed reduction of rotor length. Moving the bearings under the end turns further reduced the bearing span. Additionally, the compressor maximum aerodynamic radial load was limited to 1,600 lb. Consequently with all these improvements, the rotordynamics analysis verified that the critical speeds and the unbalance response of the motor-compressor system were within the requirements of the API standards 541 and 617(7th edition).

Detailed calculations of cooling gas flow requirements for the motor and magnetic bearings, per several operating points designated by DR, confirm the feasibility of the motor cooling circuit design, and indicate that the flow rates meet expectations for the system. Also the motor thrust load calculations confirmed that combined with the thrust loads generated by the compressor the magnetic thrust bearing design load capacity of 6,000 lb. was sufficient to handle the net thrust load. Thus the motor design data that has been generated during the last two quarters continue to confirm the feasibility of a robust motor design.

Conclusion

Efforts during the second quarter have continued to demonstrate the feasibility of the integration of a centrifugal compressor and a variable speed electric motor. Successful resolutions of some major challenges have been developed in terms of concept, methodology, and/or establishment of a design basis for the unit. These include the establishment of an aerodynamic radial load limit that will facilitate completion of the mechanical design and provide a target with which to base the configurations of the aerodynamic flowpath components. A working concept for thrust balancing has been selected and demonstrated through preliminary calculations that net thrust forces fall within acceptable limits of the proposed thrust bearing. In addition, continued evaluation of the thermodynamic cycle performance of the unit indicates that motor cooling can be successfully achieved with proper design considerations for the motor cooling circuit.

Continued progress over this reporting period shows that the technical advantages of the IEMDC over conventional technology continue to be maintained. These advantages include several key industry attributes such as operational flexibility, remote operation and automation, efficiency, reduced maintenance issues, and environmental benefits. Magnetic bearings require no lubrication; the variable speed electric motor produces no combustion by-products, and a sealed design does not allow process gas to leak into the atmosphere. It also maintains the capability to be installed in-line with the process piping and potentially in an underground vault.

The evolution of the integrated motor-compressor design continues to confirm the viability of the innovative IEMDC system. This is a very significant achievement. The successful development of this new advanced technology integrated motor-compressor system, would provide to the Natural Gas Industry, a competitive low cost and low maintenance gas compression alternative.

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List of Acronyms and Abbreviations

CFD	Computational Fluid Dynamics
c.g.	Center-of –Gravity
DR	Dresser-Rand Company
EMD	Curtiss-Wright Electro-Mechanical Corporation (EMD)
FEA	Finite Element Analysis
IEMDC	In-Line Electric Motor Driven Compressor