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Modernization of centrifugal compressors by the integration of new generation magnetic bearings.

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الإهداء

الحمد لله أولًا على نعمه وتوفيقه، الذي منحني القوة والصبر لإتمام هذا العمل.

أهدي هذا العمل إلى والديَّ العزيزين، تقديرًا لتضحياتهما ودعمهما المتواصل وتشجيعهما الدائم طوال مسيرتي الدراسية.

وإلى عائلتي الكريمة، التي كانت دائمًا مصدر دعم وتحفيز وثقة.

وإلى أساتذتي الأفاضل، الذين ساهموا في تكويني العلمي وقدموا لي التوجيه والنصح طوال مشواري الجامعي.

كما أهدي هذا العمل إلى جميع أصدقائي وزملائي الذين شاركوني لحظات الاجتهاد والمثابرة.

وإلى كل من ساهم من قريب أو بعيد في إنجاز هذا العمل.

الشكر والتقدير

الحمد لله أولًا وأخيرًا على نعمه وتوفيقه، الذي منحني القوة والصبر والعزيمة لإتمام هذا العمل.

أتقدم بخالص الشكر والتقدير إلى الأستاذ المشرف نسيب الجيلاني على توجيهاته القيمة، ودعمه المستمر، ونصائحه البناءة، ومتابعته الدائمة طوال إنجاز هذا العمل، والتي كان لها الأثر الكبير في نجاح هذه الدراسة.

كما أتوجه بالشكر إلى جميع الأساتذة الذين ساهموا في تكويني العلمي وزودوني بالمعارف والمهارات اللازمة طوال مسيرتي الجامعية.

وأتقدم بجزيل الشكر إلى جميع المهندسين والطاقم العامل الذين ساعدوني خلال هذا العمل، على تعاونهم وتقديمهم للمعلومات والتوجيهات القيمة.

كما لا يفوتني أن أعبر عن امتناني العميق لعائلتي على دعمهم المتواصل وتشجيعهم الدائم طوال فترة الدراسة.

وأتوجه كذلك بخالص الشكر والتقدير إلى كل من ساهم من قريب أو بعيد في إنجاز هذا العمل، وساعدني بكلمة طيبة أو نصيحة أو دعم معنوي.

وفي الأخير، أتقدم بالشكر إلى كل أصدقائي وزملائي الذين ساندوني وساهموا، بطريقة مباشرة أو غير مباشرة، في إنجاز هذا العمل.

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L I S T O F A B B R E V I A T I O N S / S Y M B O L S

LIST OF ABBREVIATIONS / SYMBOLS

Abbreviation	Significance
HVAC	Heating, Ventilation ,and Air Conditioning
AMB	Active Magnetic Bearings
S2M	Société de Mécanique Magnétique
SKF	Svenska Kullagerfabriken
SEP	Société Européenne de Propulsion
PID	Proportional–Integral–Derivative (Controller)
E300V2	Electronic Control Unit Model (Magnetic Bearing Controller)
PMB	Passive Magnetic Bearings
HMB	Hybrid Magnetic Bearings
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
N	Number of failure
T	Total operating time
A	Availability
Tr	Total repair time
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
P	Power consumption
H	Operating hours
Ce	Energy cost per unit
TCO	Total Cost of Ownership
DZD	Algerian Dinar
RBM	stands for Revolutions Per Minute.
DGS	Dry Gas Seal
ΔP	Pressure Difference

ABSTRACT

ABSTRACT

This study highlights the economic and operational advantages that the use of magnetic bearings in centrifugal compressors within the oil and gas sector can provide. The techno-economic evaluation shows a 16.64% reduction in maintenance costs. This reduction represents total savings estimated at approximately 673,372,329 DZD over the compressor life cycle. The analysis also indicates a 26.74% reduction in the overall life cycle cost. This result demonstrates a significant improvement in the system's overall profitability. The total financial benefit is estimated at 1,003,854,999 DZD, confirming a positive long-term economic impact. These savings are mainly due to the elimination of additional oil lubrication systems. They are also attributed to the reduced frequency of replacement of wear-prone parts and maintenance operations. Furthermore, magnetic bearings enhance compressor reliability and availability by reducing friction, vibration, and wear.

In summary, this technology improves performance, lowers total cost of ownership, and increases industrial efficiency.

Keywords: Centrifugal compressors; conventional bearings; magnetic bearings; dry gas seals; techno-economic analysis; total cost of ownership (TCO).

RESUME

Cette étude montre les avantages économiques et opérationnels que l'utilisation des paliers magnétiques dans les compresseurs centrifuges du secteur pétrolier et gazier peut apporter L'évaluation technico-économique montre une baisse de 16,64 % des coûts de maintenance Cette réduction représente une économie globale estimée à environ 673 372 329 DZD sur le cycle de vie du compresseur. L'analyse précise également un pourcentage d'économie du coût global du cycle de vie de 26,74 %.Ce résultat témoigne d'une amélioration sensible de la rentabilité globale du système. La bénéfice financier total est évalué à 1 003 854 999 DZD confirmant la rentabilité économique positive à long terme. Ces économies sont dues essentiellement à la suppression des systèmes supplémentaires de lubrification à huile. Ils sont également dus à la diminution de la fréquence de remplacement des pièces sujettes à l'usure et des opérations de maintenance.

Par ailleurs, les paliers magnétiques renforcent la fiabilité et la disponibilité des compresseurs en atténuant les frottements, les vibrations ainsi que l'usure. En résumé, cette technologie maximise les performances, diminue le coût total de possession et accroît l'efficacité industrielle.

Mots clés : Compresseurs centrifuges ; paliers conventionnels ; paliers magnétiques ; joints à gaz secs ; analyse technico-économique ; coût total de possession (TCO).

الملخص:

تُبرز هذه الدراسة المزايا الاقتصادية والتشغيلية لاستخدام المحامل المغناطيسية في الضواغط الطاردة المركزية ضمن قطاع النفط والغاز. وتُظهر نتائج التقييم التقني-الاقتصادي انخفاضًا في تكاليف الصيانة بنسبة 16.64%، وهو ما يمثل وفورات إجمالية تُقدَّر بحوالي 673,372,329 دينار جزائري خلال دورة حياة الضاغط. كما تشير النتائج إلى انخفاض في التكلفة الإجمالية لدورة الحياة بنسبة 26.74%، مما يعكس تحسنًا ملحوظًا في ربحية النظام بشكل عام. ويُقدَّر العائد المالي الإجمالي بـ 1,003,854,999 دينار جزائري، وهو ما يؤكد وجود أثر اقتصادي إيجابي على المدى الطويل. وتعود هذه الوفورات بشكل أساسي إلى الاستغناء عن أنظمة التزييت الزيتي الإضافية، بالإضافة إلى تقليل تكرار استبدال الأجزاء المعرضة للتآكل، والحد من عمليات الصيانة الدورية. علاوة على ذلك، تُسهم المحامل المغناطيسية في تحسين موثوقية الضواغط وزيادة جاهزيتها التشغيلية، من خلال تقليل الاحتكاك والاهتزاز والتآكل.

وخلاصةً، تُحسن هذه التقنية الأداء العام، وتخفض التكلفة الإجمالية للملكية، وترفع من كفاءة الأنظمة الصناعية.

الكلمات المفتاحية: الضواغط الطاردة المركزية، المحامل التقليدية، المحامل المغناطيسية، الأختام الغازية الجافة، التحليل التقني-الاقتصادي، التكلفة الإجمالية للملكية.

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Centrifugal compressors are among the most important rotating machines used in the oil and gas industry due to their major role in gas transportation, processing, and storage systems. Their performance directly affects production continuity, operational reliability, energy consumption, and maintenance costs. For this reason, improving the efficiency and reliability of centrifugal compressors has become a major industrial and technological challenge.[3.4].

Conventional centrifugal compressors generally operate using oil-lubricated bearing systems. Although these systems are widely used in industrial applications, they present several limitations related to mechanical friction, wear, vibration, lubrication requirements, and frequent maintenance operations. In addition, oil lubrication systems increase operational complexity and may generate environmental and safety concerns due to leakage risks and auxiliary equipment requirements.[3.6].

In recent years, magnetic bearing technology has emerged as an advanced solution for improving the performance of high-speed rotating machinery. Unlike conventional bearings, magnetic bearings operate without mechanical contact, which significantly reduces friction losses and mechanical wear. Their integration into centrifugal compressors contributes to improved dynamic stability, reduced vibration levels, enhanced operational reliability, and lower maintenance requirements. Moreover, the use of dry gas seals together with magnetic bearings allows the elimination of oil lubrication systems, resulting in cleaner and more efficient compressor architectures.[10-12].

The main objective of this thesis is to study, from a theoretical, technical, and techno-economic perspective, the contribution of new-generation magnetic bearings in centrifugal compressors. Within this framework, a comparative techno-economic analysis will be carried out between a centrifugal compressor equipped with conventional bearings installed in the TFT region and a centrifugal compressor fitted with magnetic bearings installed in the HRL region. The purpose of this study is to evaluate the impact of magnetic bearing technology on the technical performance of compressors, their energy efficiency, operational reliability, maintenance requirements, and energy consumption under real industrial operating conditions. Particular attention will be given to the integration of dry gas seals and their role in improving compressor operation as well as reducing maintenance constraints.

Furthermore, the study will focus on the evaluation of the total Life Cycle Cost, considered as the main criterion for the economic comparison between the two technologies. The analysis will also take into account the impact of downtime, maintenance costs, and energy losses on the profitability and operational availability of the installations. Through this comparative approach, the thesis aims to highlight the technical and economic advantages of magnetic bearings and to identify the most suitable solution for improving the overall performance of centrifugal compressors while reducing long-term operating costs (Despite the limited information available within Sonatrach on conventional bearing compressors and magnetic bearing compressors, we have decided to carry out a technical and economic study to compare these two categories of compressors. It should be emphasized that the compressors chosen for this study have a heterogeneity with regard to their characteristics and specifications. Nevertheless, the objective of this comparison is to highlight the technical and economic advantages of compressors with magnetic bearings, while demonstrating their relevance compared to traditional bearing compressors).

This thesis is composed of four complementary chapters followed by a general conclusion.

The first chapter, entitled “Theoretical and Technical Foundations of Centrifugal Compressors,” presents the operating principles, the main constituent components, and the technical characteristics of centrifugal compressors.

The second chapter, entitled “Study of Compressors Equipped with Conventional Bearings,” focuses on the analysis of conventional bearing systems by highlighting their operating principles, technical characteristics, advantages, and operational limitations.

The third chapter, entitled “Study of Compressors Equipped with Magnetic Bearings,” is devoted to magnetic bearing technology, particularly their operating principles, command and control systems, as well as the technical advantages they provide in rotating machinery applications.

The fourth chapter, entitled “Techno-Economic Comparative Analysis of Centrifugal Compressors Equipped with Conventional Bearings and Magnetic Bearings,” provides a detailed comparative analysis of the two technologies based on technical and economic criteria in order to evaluate their performance, reliability, maintenance requirements, and impact on operating costs.

Finally, this work conclude with a general conclusion.

ChapterI

Theoretical Foundations and Technological Developments in Centrifugal Compressors

I.1. INTRODUCTION

Turbo machinery represents a fundamental category of rotating mechanical systems widely used in modern industrial processes. These machines operate based on the continuous exchange of energy between a rotating component and a working fluid, allowing the conversion of mechanical energy into fluid energy or vice versa. Turbo machines play a critical role in numerous sectors including power generation, oil and gas processing, petrochemical industries, and large-scale industrial refrigeration systems From a mechanical and thermodynamic perspective, turbo machinery involves complex interactions between fluid dynamics, rotor mechanics, and energy transfer mechanisms. The performance of these machines depends on several parameters such as rotational speed, flow rate, pressure ratio, aerodynamic efficiency, and mechanical stability. Consequently, understanding the fundamental principles governing turbo machinery is essential for analyzing their operational behavior, efficiency, and reliability [3].

Among the different categories of turbo machines, compressors occupy a particularly important position in industrial applications. Their primary function is to increase the pressure of gases by converting mechanical energy supplied by a rotating shaft into kinetic and pressure energy within the fluid. This compression process is achieved through specific aerodynamic components such as impellers, diffusers, and volutes, which guide and control the fluid flow within the machine.

In order to better understand the technological evolution and operational characteristics of compressors, it is necessary to examine their classification according to their working principles, as well as the main industrial domains in which they are applied. The following sections therefore present the principal categories of compressors and their major fields of industrial application [4].

I.2. HISTORY OF COMPRESSORS

The evolution of compressors is closely linked to the progressive development of energy technologies and thermodynamic systems applied in industrial processes. The earliest forms of compression date back to antiquity, prior to the 1st century, when simple devices such as bellows were used in metallurgy to increase airflow and intensify combustion processes. With the advent of the Industrial Revolution during the 18th century (1760–1840), significant technological advancements led to the development of the first mechanical compressors, primarily piston-based systems operating according to a positive displacement principle. These machines became widely used throughout the 19th century, particularly with the expansion of steam-powered technologies, and remained dominant until the early 20th century.

During the 20th century, particularly between the 1920s and 1950s, the development of turbo machinery marked a major transition toward dynamic compression systems, such as centrifugal and axial compressors. These machines enabled higher mass flow rates and continuous operation, meeting the increasing demands of large-scale industrial applications, especially in the oil, gas, and energy sectors [6].

I.3. DEFINITION AND ROLE OF COMPRESSORS

A compressor is a mechanical device designed to increase the pressure of a gas by reducing its volume. This process is necessary in many industrial sectors, in particular in the production of compressed air, refrigeration, air conditioning, natural gas transportation, as well as in internal combustion engines.

By raising the gas pressure, compressors enable it to be transported, stored, or used efficiently in various industrial processes. They are also integrated into such complex systems as gas turbines and jet engines [2].

I.4. CLASSIFICATION OF COMPRESSORS

Compressors are fundamental mechanical systems designed to increase the pressure of gases for a wide range of industrial, energy, and technological applications. The compression process is achieved either by reducing the gas volume within a confined space or by imparting kinetic energy to the fluid and subsequently converting it into pressure energy .Due to the variability of operating conditions, performance requirements, and industrial applications, compressors are classified according to several engineering criteria, including operating principle, pressure range, structural configuration, and functional application. This classification provides a systematic framework for understanding the operational behavior, efficiency, and technological limitations of different compressor types, and it serves as a foundation for selecting the most suitable machinery for specific industrial needs [7].

I.4.1. Classification According to Operating Principle

From a thermodynamic and mechanical perspective, compressors are fundamentally divided into two principal categories:

I.4.1.1. Positive Displacement Compressors

Positive displacement compressors operate by trapping a fixed quantity of gas within a confined space and mechanically reducing its volume, thereby increasing its pressure. Compression occurs intermittently, and the pressure rise is directly related to volume reduction rather than fluid velocity.

Typical examples include reciprocating, rotary screw, and vane compressors. These machines are particularly suitable for applications requiring high pressure ratios and moderate flow rates, as they provide stable delivery and precise pressure control. It is divided into two main types:

I.4.1.1.1. Reciprocating Compressors

These compressors use one or more reciprocating pistons to compress the gas inside a cylinder. The gas enters the cylinder through the intake valve, and then is compressed by the piston movement, to be subsequently expelled through the exhaust valve.

Reciprocating compressors are widespread in small and medium-sized applications, especially in refrigeration systems, industrial air compressors, and petroleum industry applications. They can reach very high pressures up to several hundred bars, however, their flow rate is relatively low. Also, the process of their operation generates significant vibrations, which requires careful balancing and regular maintenance [2].

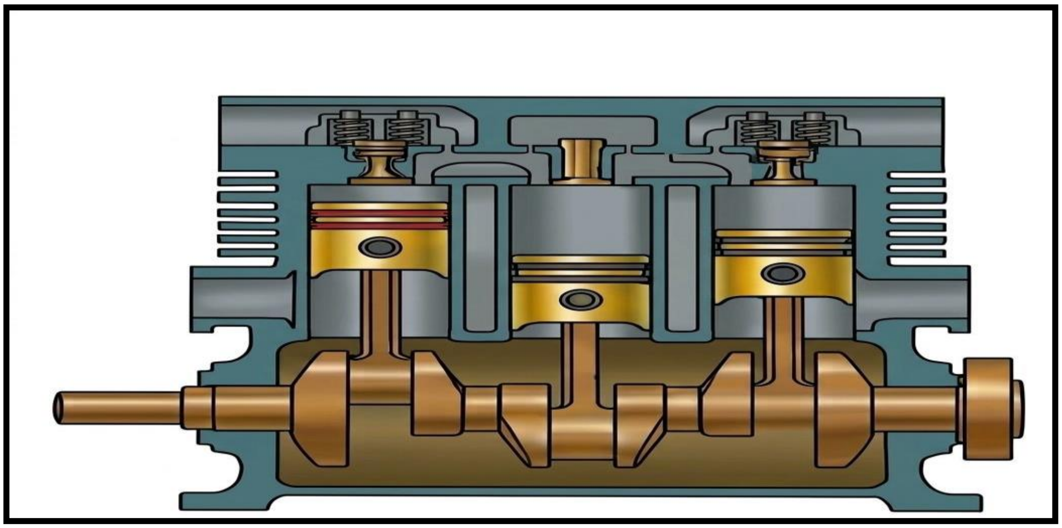

Fig.I.1. Reciprocating Compressors [14].

I.4.1.1.2. Screw compressors

This model is one of the most widely used compressors in factories. It works by using helical screws instead of a piston. The pressure provided by this type of equipment is usually in the range of 5 bars for a single-stage model, and 13 bars for multi-stage devices. The spiral compressor can be operated continuously, as it has an operating ratio of up to 100% [2].

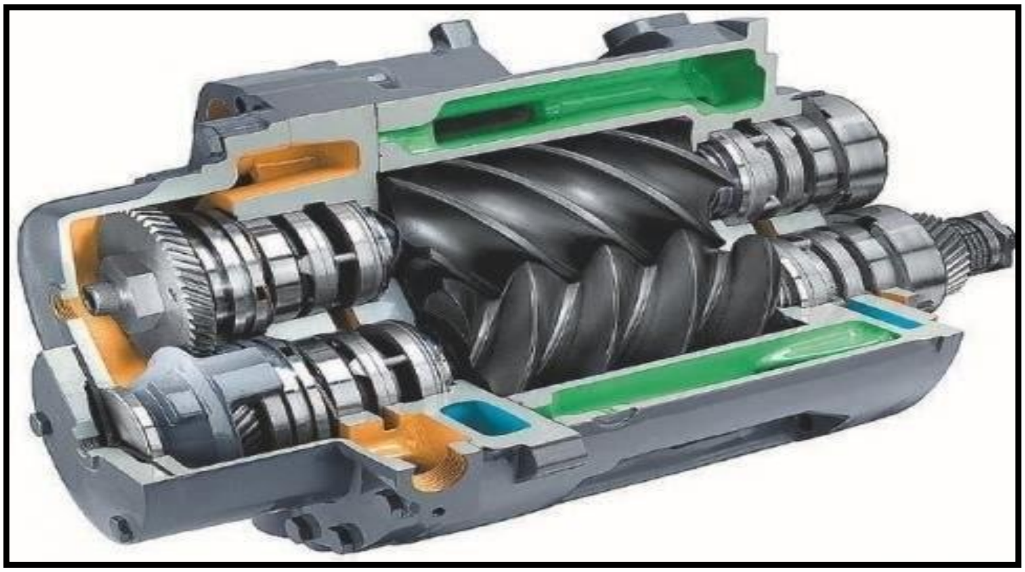

Fig.I.2. Screw compressors [03].

I.4.1.2. Dynamic Compressors

Dynamic compressors function by continuously accelerating the gas using rotating elements and converting the resulting kinetic energy into pressure through diffusers or stator passages. Unlike positive displacement machines, the flow process is continuous. This category includes centrifugal, axial, and mixed-flow compressors, which are particularly appropriate for large flow rates and steady industrial processes.They are divided into two main types:

I.4.1.2.1. Axial compressors

The axial compressors are not cooled, the compression is made without exchange of warmth with the outside.They are receiving machines with axial flow of the compressible, they are used in the high-power turbines and in aviation turbojet engines, they are characterized by the large number of stages and the compression ratio is not high [3].

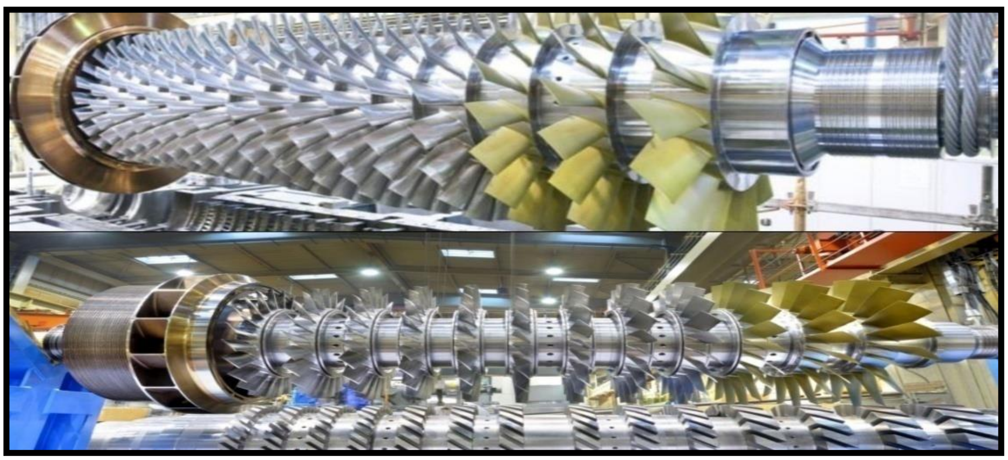

Fig.I.3. Axial compressors [3].

I.4.1.2.2. Centrifugal compressors

These compressors are widely used in refining and in the chemical and petrochemical industry; they are very compact and can develop significant powers compared to their size; in their operating range, they do not generate pressure pulsation at the piping level; these qualities allow lightweight installations, for the environment of these compressors

They are particularly appreciated for their reliability, because by their design, these machines do not generate any metal-on-metal friction; the frequency of interviews usually reaches from three to five years.

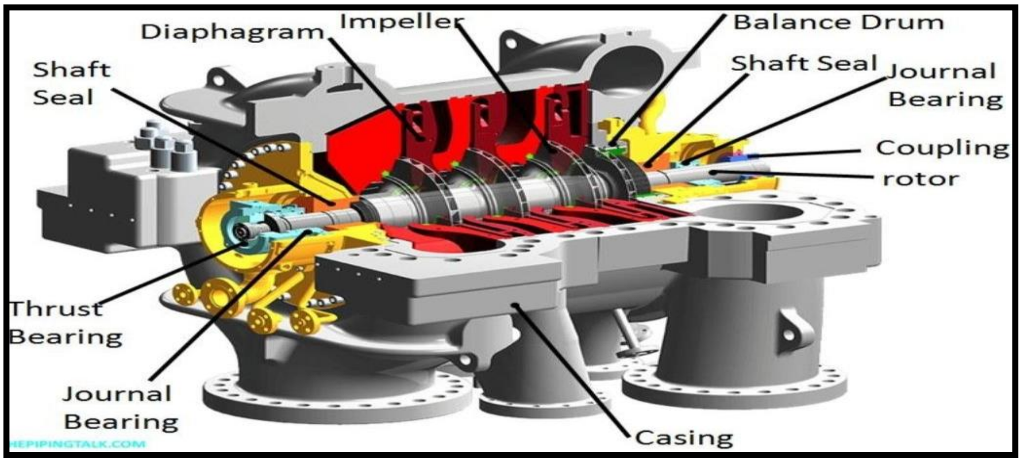

Fig.I.4. Centrifugal compressors **[**8].

I.4.2. Classification According to Pressure Range

Another important classification criterion is the discharge pressure level, which determines the suitability of a compressor for a given process. Compressors are commonly grouped as:

- Low-pressure compressors (up to approximately 3 bar)
- Medium-pressure compressors (approximately 3–10 bar)
- High-pressure compressors (above 10 bar)

This classification plays a significant role in equipment selection, system design, and safety considerations [4 -16]

I.4.3. Classification According to Mechanical Design

Compressors can be classified based on their mechanical design and type. Common mechanical distinctions include single-stage versus multistage configurations and horizontally versus vertically split casings, which affect maintenance accessibility, structural strength, and thermal behavior.

In terms of type, compressors are generally axial or centrifugal. Axial compressors direct the fluid parallel to the rotation axis through multiple stages of rotating and stationary blades, while centrifugal compressors accelerate the fluid radially outward, converting kinetic energy into pressure. Understanding both design and type is essential for predicting performance and selecting appropriate industrial applications.

I.5. OPERATING PRINCIPLE OF COMPRESSORS

A compressor is a mechanical device that increases the pressure of a gas (usually air) by reducing its volume or increasing its velocity, thereby converting mechanical energy into pressure energy. It operates by drawing in the gas, compressing it within a chamber (such as a piston, screw, or scroll mechanism), and then delivering it to a storage tank or system.

The operation of a compressor can be described through three main stages:

I.5.1.Suction

The gas is drawn into the compression chamber through an intake valve.

I.5.2.Compression

The volume of the chamber decreases due to the movement of a piston or the rotation of screws or scroll elements, resulting in an increase in both pressure and temperature of the gas.

I.5.3. Discharge

The compressed gas is expelled through a discharge valve and directed toward a storage tank or distribution system.

I.6. TYPES OF COMPRESSORS

Compressors can be classified into two categories according to their mode of operation: positive displacement compressors and dynamic compressors. Each of these types have characteristics, operating principles and applications

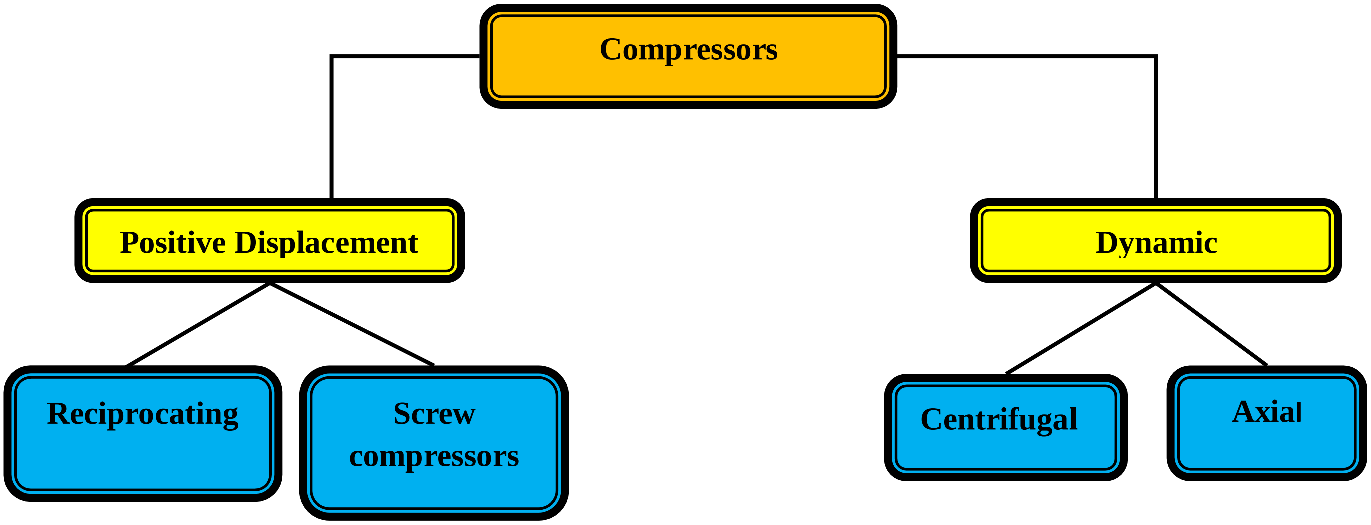

Fig.I.5. General Classification of Compressors

I.7. PERFORMANCE CHARACTERISTICS OF COMPRESSORS

The performance of a compressor is evaluated through several fundamental parameters that make it possible to size, choose and operate these machines efficiently in an industrial context. A good understanding of these characteristics is essential to avoid critical operating conditions such as pumping, while optimising energy efficiency. They can be divided into several types [4].

I.7.1. Volume flow rate

The volume flow rate represents the volume of gas sucked in or discharged per unit of time, generally expressed in(m^3/s). It makes it possible to evaluate the capacity of the compressor.

I.7.2. Mass flow rate

The mass flow rate corresponds to the mass of gas circulating through the compressor per unit of time (kg/**s**). It is more accurate because it does not depend on pressure and temperature variations.

I.7.3. Compression ratio

The compression ratio is defined as the ratio between the discharge pressure and the suction pressure. It characterizes the pressure rise provided by the compressor.

I.7.4. Power consumption

The power absorbed is the power supplied to the compressor by the engine to ensure its operation. It depends on the operating conditions and the properties of the fluid.

I.7.5. Isentropic efficiency

The isentropic efficiency makes it possible to evaluate the efficiency of the compressor by comparing the real compression with an ideal isentropic compression.

I.8. INDUSTRIAL APPLICATIONS

Compressors play a critical role in modern industry, where they are used to transport, pressurize, and process gases under controlled conditions. Their applications span multiple sectors, and the selection of a specific compressor type depends on factors such as required pressure ratio, flow rate, gas properties, efficiency, and operational reliability [4].

I.8.1. Oil and Gas Industry

Compressors are widely used for gas gathering, pipeline transportation, gas reinjection, and processing operations. High-capacity centrifugal compressors are commonly employed due to their ability to handle large flow rates and operate continuously.

I.8.2. Power Generation

In power plants, compressors are utilized in gas turbines, combustion air systems, and cooling processes. Their efficiency directly affects plant performance and energy consumption.

I.8.3. Chemical and Petrochemical Industry

Compressors are essential for gas circulation, chemical reactions, vapor recovery, and synthesis processes. Equipment selection must ensure safety, corrosion resistance, and operational stability.

I.8.4. Manufacturing and Industrial Utilities

Compressed air systems are used in pneumatic tools, automation systems, instrumentation, and production lines. Rotary and reciprocating compressors are typically employed depending on pressure and load variation.

I.8.5. Refrigeration and HVAC Systems

Compressors are the core component of refrigeration cycles, enabling refrigerant circulation and heat transfer. Their performance strongly influences system efficiency and thermal control.

I.9. Centrifugal Compressors

A centrifugal compressor is a turbo machine in which the gaseous fluid flows mainly in a radial direction. The increase in gas pressure is achieved through the energy imparted by the blades of a rotating impeller. These blades, arranged on the lateral surface of the wheel, form flow channels constituting the blade system.

Mechanical energy is transmitted to the impeller through the shaft. Part of this energy is directly converted into pressure within the impeller itself, while the remaining portion is transformed in the stator, particularly within the diffusers.

Although the theory of centrifugal compressors has been established for a long time, their large-scale industrial application only truly developed between 1945 and 1950. Today, their production exceeds that of reciprocating compressors for several major reasons:

The continuous increase in the size of chemical plants requires ever-larger volumes of compressed gas, favoring the use of centrifugal compressors [3].

- A single centrifugal compressor can often replace several reciprocating compressors.
- The compression process is generally oil-free, preventing any contamination of the gas.
- Low pressure pulsations reduce the need for heavy and costly foundations.

However, these compressors also present certain disadvantages compared to reciprocating models, particularly in terms of efficiency, which is around 77% depending on the configuration.

Furthermore, their operation requires highly qualified personnel capable of detecting early signs of malfunction, such as abnormal variations in rotor vibration levels. Therefore, systematic monitoring and control operations play a crucial role in ensuring the reliability and performance of these machines [3].

I .9.1. Operating Principle Of Centrifugal Compressors

I.9.1.1. Energy Transfer Mechanism

The operation of a centrifugal compressor is fundamentally based on the transfer of mechanical energy from a rotating shaft to the working fluid. This energy originates from an external prime mover, such as an electric motor or turbine, which drives the compressor shaft and impeller at high rotational speed. As the impeller rotates, it imparts kinetic energy to the gas through centrifugal action and blade interaction.

The gas particles are forced outward from the impeller eye toward the periphery, resulting in a substantial increase in velocity. This rise in kinetic energy represents the first stage of energy transfer within the compressor. The efficiency of this process depends on several parameters, including rotational speed, impeller geometry, blade angle, and gas properties. Therefore, the energy transfer mechanism constitutes the core principle governing the performance and pressure-generating capability of centrifugal compressors [9].

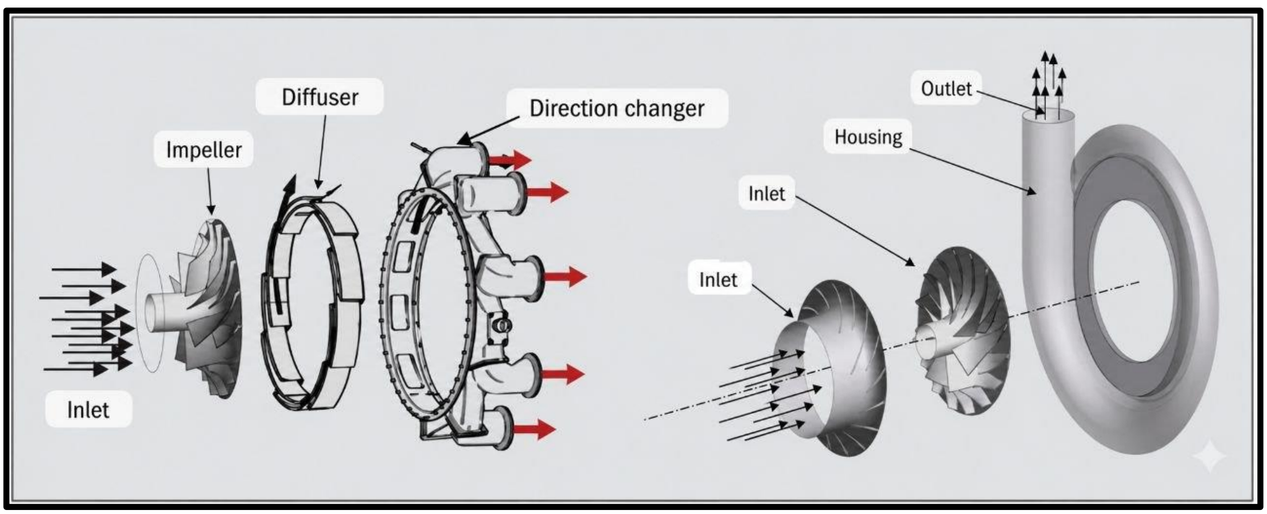

Fig.I.6. Operating principle [8].

I.9.1.2. Flow Path Through the Compressor

A centrifugal compressor transfers energy to a fluid by increasing its velocity and converting it into pressure. The fluid follows a continuous path through several key stages, each of which plays a specific role in the pressure rise and stable operation of the compressor. The main stages are described below:

- **Inlet:** The working fluid enters the compressor through the inlet, where it is guided smoothly toward the impeller.

- **Impeller:** In the impeller, the fluid is accelerated radially outward, gaining kinetic energy.

- **Diffuser:** The fluid passes through the diffuser, where its velocity decreases and kinetic energy is converted into pressure.

- **Volute:** Finally, the compressed fluid is collected in the volute, which directs it toward the downstream system.

Each stage contributes to efficient energy transfer, pressure increase, and stable operation.

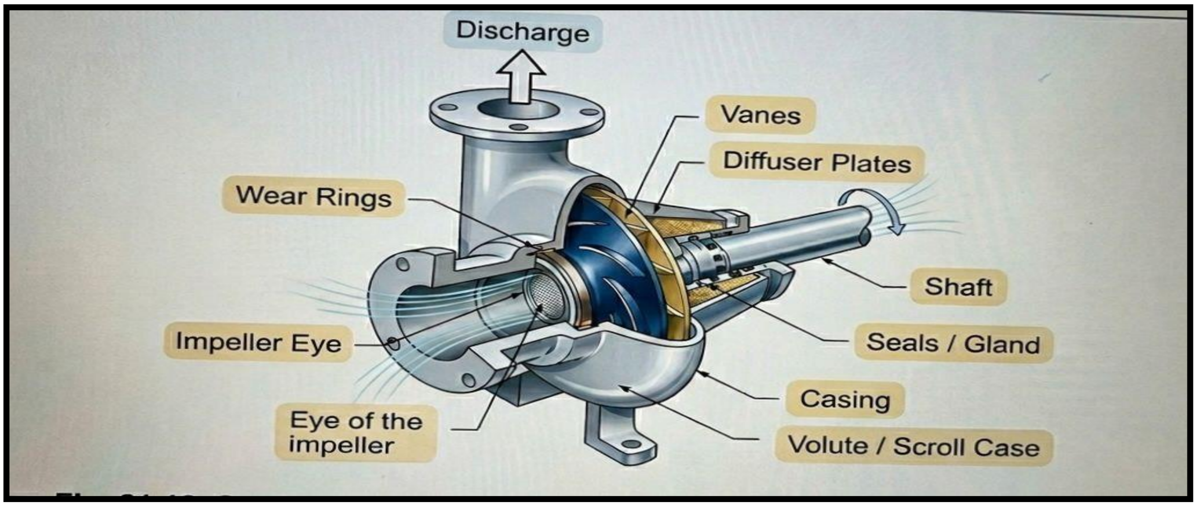

Fig.I.7. Flow Path Through the Compressor [3].

I.9.1.3. Pressure Rise Mechanism

The pressure rise mechanism in a centrifugal compressor results from the combined action of the impeller and the diffuser. The impeller accelerates the fluid radially outward, increasing its kinetic energy. The diffuser then decelerates the high-velocity fluid, converting kinetic energy into static pressure. Finally, the volute collects the compressed fluid and guides it toward the discharge, ensuring smooth flow and minimal energy loss.

This mechanism depends on both rotor design (blade geometry, rotational speed) and stationary components (diffuser shape, volute configuration),which determine the achievable pressure ratio, efficiency, and flow stability. Proper understanding and optimization of this mechanism are essential for industrial application and compressor performance prediction.

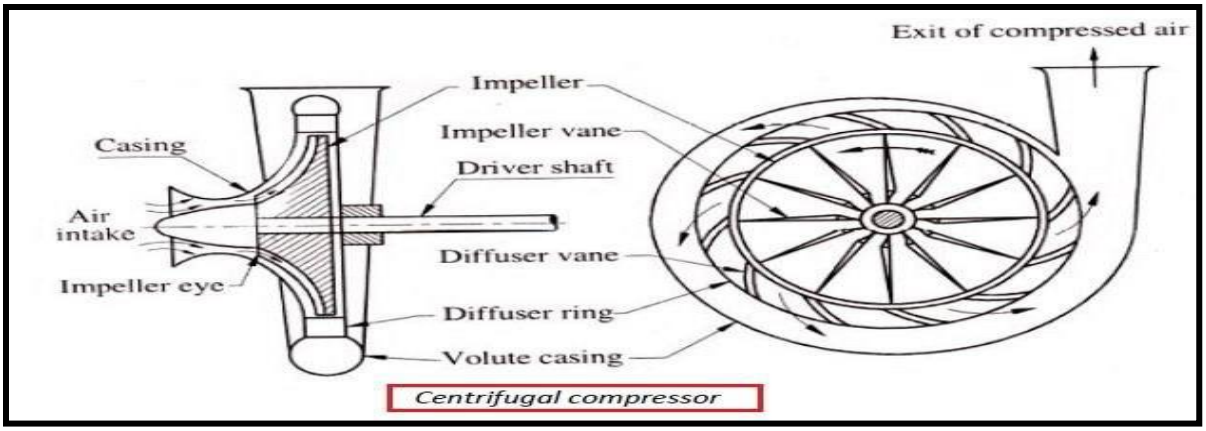

Fig.I.8. Pressure Rise Mechanism [4].

I.9.2. Types and classification of centrifugal compressors

There are two main types of centrifugal compressors in depending on the shape of the body (body) and the joint plane.

• Type **BCL:** Centrifugal compressors with a body (body) to vertical joint plane that can operate at very high pressure values high. The barrel-shaped bodies, usually forged, are closed by one or two flanges.

• Type **MCL:** Centrifugal compressors with a body (body) to horizontal joint plane capable of operating at pressure values not very high. The two-part bodies, usually forged, are assembled by several studs [14].

I.9.2.1. Compressors with vertically open bodies (BCL)

The vertically open bodies consist of a cylinder closed at the ends by two flanges. It is for this reason that this type of compressor is called "barrel".These compressors, generally multi-stage, can operate athigh pressures (up to 700 kg/cm^2).

The rotorandthe diaphragmslocatedinsidethe the body do not differ fundamentally from those of the MCL compressors [5].

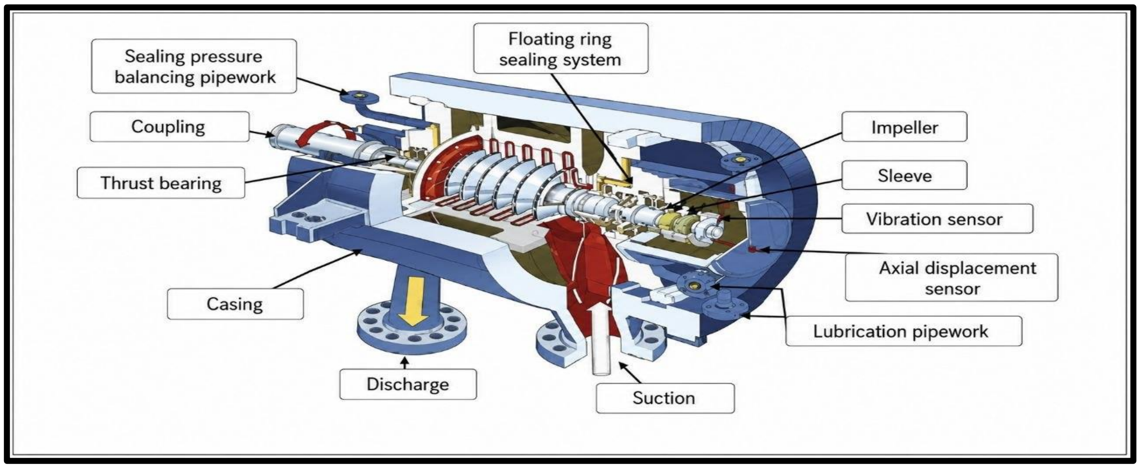

Fig.I .9. Main components of a centrifugal compressor with a joint plane vertical (BCL) [14].

I.9.2.2. Centrifugal compressor with flat seal casing horizontal (MCL)

These compressors generally operate at low pressures (below 60 bar) and high flow rates. The horizontally open body consists of half-bodies united on the horizontal joint plane. Compressors with horizontally open bodies are indicated by the sign MCL and can be subdivided according to their turn according to the number of sections [3].

- **MCL** Compressors.
- **2MCL** Compressors.
- **3MCL** Compressors.

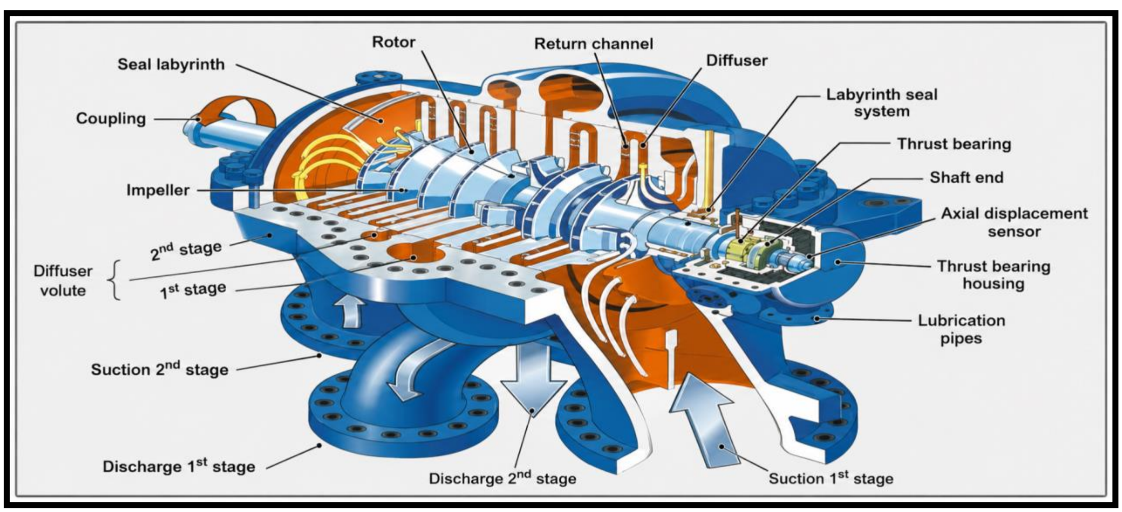

Fig.I .10. Main components of a centrifugal compressor with a horizontal joint plane (2MCL) [14].

I.9.3. Industrial applications of centrifugal compressor

Centrifugal compressors are widely used in many industrial sectors due to their ability to provide high flow rates and continuous operation. In the oil and gas industry, they are used for the transport and compression of natural gas through pipelines, as well as in processing units.

In the field of energy production, these compressors are integrated into gas turbines, where they participate in the compression of the air before combustion. They also play an essential role in the chemical and petrochemical industries, in particular for handling process gases and maintaining the pressure conditions necessary for reactions.

In addition, centrifugal compressors are used in large-capacity refrigeration and air conditioning systems, as well as in certain industrial applications requiring large-scale ventilation or air compression. Their reliability, their efficiency and their ability to operate continuously make them essential equipment in modern installations [5].

I.10. CONCLUSION

This chapter has presented the theoretical principles related to compressors, with particular emphasis on centrifugal compressors. It has examined their operating principles, fundamental components, classification, as well as their various industrial applications. All of these elements provide an essential theoretical foundation for understanding the behavior of these machines and their performance under different operating conditions.

It is important to note that the overall performance, reliability, and service life of centrifugal compressors are largely dependent on the configuration of the bearing system employed. Indeed, these machines may be equipped with either conventional bearings or magnetic bearings, each offering specific technological characteristics as well as distinct operational advantages [3-4-6].

In this context, the following chapter will provide an in-depth analysis of conventional bearing systems in order to clarify their operating principles, compare them with alternative technologies, and highlight their impact on the performance of centrifugal compressors.

ChapterII

Analysis of Centrifugal Compressors with Conventional Bearings

II.1. INTRODUCTION

Centrifugal compressors are an essential category of rotating machines used in many industrial sectors, including petrochemicals, power generation and refrigeration systems. At the heart of these machines, the shaft support system plays a fundamental role in overall reliability and performance. Centrifugal compressors equipped with conventional bearings generally use plain (or hydrodynamic) bearings, lubricated by an oil film.

Conventional bearings are distinguished by their robustness, their ability to withstand high loads and their relatively controlled cost. However, they require a complex lubrication system and regular maintenance in order to avoid wear and failure. Despite the emergence of alternative technologies such as magnetic bearings, conventional bearings remain widely used due to their technological maturity and proven reliability.

Thus, the study of centrifugal compressors with conventional bearings is essential to understand the issues related to the performance, maintenance and service life of industrial equipment.

II.2. DEFINITION

Bearings are machine components used to guide the rotating shafts. There are two main families of bearings: plain bearings and rolling bearings. In the former, the shaft bears on a bushing and is separated there from by a lubricating film; in the latter, rolling bodies (balls or rollers) separate the rotating ring from the outer bore. According to the direction of the load relative to the rotating shaft. In general, a bearing is defined as the fixed part of a machine that supports a moving part [1].

II.3. DEFFERNT TYPES OF BEARINGS

II.3.1. Hydrodynamic bearings

A hydrodynamic bearing consists of a shaft which rotates inside a fixed bearing separated from it by a lubricating fluid. The shaft movement has a certain eccentricity with respect to the bearing; it thus forms a convergent and a divergent in the fluid. The rotation of the shaft drives the fluid into the converging corner and creates a hydrodynamic pressure field which opposes the load and the equilibrium. The maximum speed of a hydrodynamic bearing supporting a shaft with a diameter of 100 mm and a maximum load of 400 kN can reach 60,103 rpm. However, the use of hydrodynamic bearings results from the supercritical speed thresholds beyond which they make the system unstable, which results from the coupling terms of the rigidity of the oil film.

This instability, called "Oil whip", appears at a speed equal to twice the first critical speed of the rotor and is characterized by a sub-synchronous speed which dangerously degrades the performance of the mechanical assembly.

Fig .II.1. Hydrodynamic bearing [17].

II.3.2. Plain bearings

Plain bearings are frequently used, but their operating principles are more complex. Plain bearings consist of one or more parts. The bearing surfaces of the shaft are bearings in bronze or soft cast iron, with an inner radius IR and a length L. The part of the shaft borne by the bearing is the trunnion, the outer part is the sleeve.

If the journal and the sleeve are made of steel with a roughness Ra, even with good lubrication the bearing surfaces can rub against each other and cause the machine to seize. Therefore, the trunnions of most bearings are made of brass, bronze or antifriction metal.

Trunnions are usually lubricated under pressure. They are often striated for an even distribution of the lubricant over the entire surface. Smooth bearings are found in thermal engines, compressors, turbomachines,alternators and reducers, etc.

Fig.II.2. Plain bearing [1].

II.3.3. Oscillating roller bearings

Oscillating roller bearings are exceptionally stable; their reaction is complex. They are composed of (n) pads, which may or may not be identical, individually articulated around the pivots, and are generally located on a circle called (circle of pivots). The shoes rotate around their pivots occupying a static equilibrium position such that the hydrodynamic action exerted on each shoe under dynamic conditions, follow the movement of the shaft, this is at the origin of the stability of this bearing.

Fig.II.3. Oscillating roller bearings [1].

II.3.4. Aerodynamic bearings

Aerodynamic thrust bearings and bearings work on the same principles as those lubricated with oil. Their particularity comes from the very low viscosity of the lubricating gases, both advantage and disadvantage, to which are added the specificities brought by compressibility. They are therefore used in high-precision and small-sized machines where high rotational speeds are combined with very low clearances (measuring devices, medical industry).

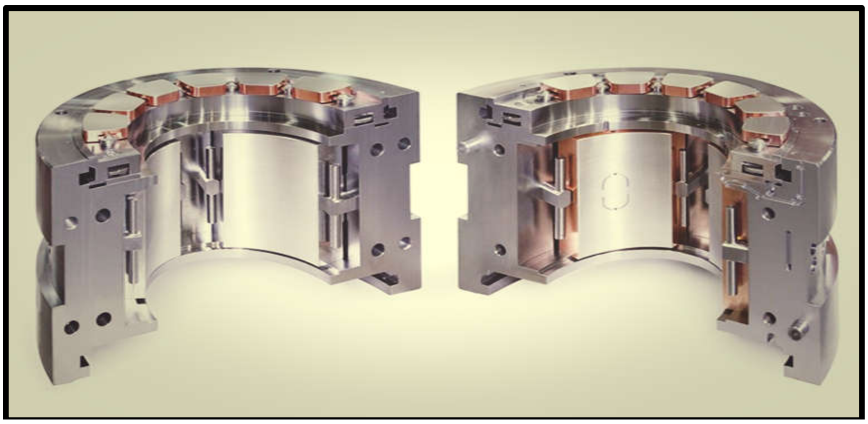

Fig.II.4. Aerodynamic bearings [8].

II.3.5. Hydrostatic bearing

Hydrostatic bearings are bearing systems, due to their extremely high and almost wear-free precision, which are found in precise mechanical engineering applications and measurement and control tools. The function is based on the fact that by an external pressure supply, the lubricating liquid leaving the inlet channels is pressed continuously into the chambers between the surfaces of the bearings. These bearing surfaces are always separated by a thin lubricating film, to avoid any friction of the bearing surfaces. This allows a very precise adjustment of the positioning within the micrometer limit. Compared to other types of support, the essential difference is that there is never any contact between the two surfaces since an external pump allows the introduction of liquid under pressure inside the contact zone and therefore ensures the permanent existence of a lubricating film even at zero speed.

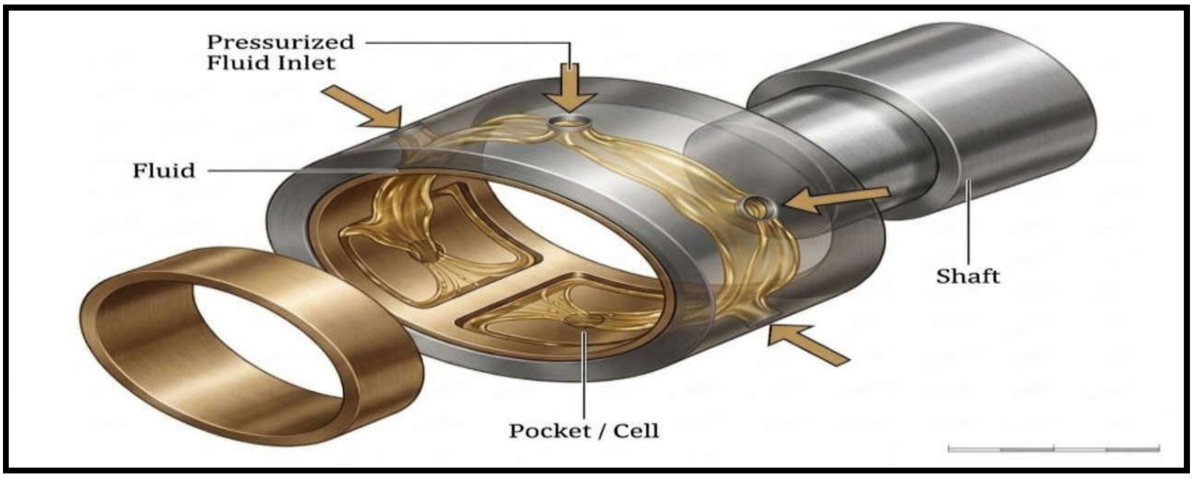

Fig.II.5.Hydrostatic bearing [1].

II.3.6. Three-pad hydrostatic bearing

In any hydrostatic device, one of the two facing surfaces is smooth while the other comprises one or more cavities (or cells) connected to a pressure generator. In our studies, we consider a hydrostatic bearing consisting of three cells. The (Figure.II.6) represents the elements which form a hydrostatic bearing with 3 shoes, controlled and powered by three hydraulic resistors. The three-shoe hydrostatic bearing consists of two parts:

- A fixed part: represented by three identical pads, where each pad has a central cell which is controlled and supplied by a capillary type of hydraulic resistance.
- A moving part: represented by the moving grain.

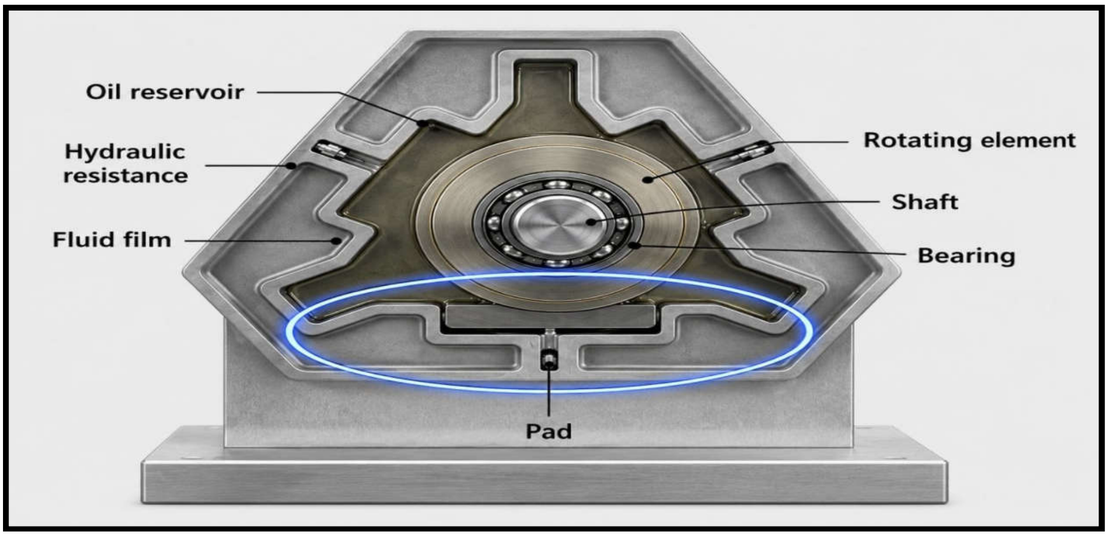

Fig.II.6. Three-pad hydrostatic bearing [1].

II.4. THE AREAS OF USE BEARINGS

II.4 .1. Rotor

The rotor part of the centrifugal compressor is composed by the shaft, the wheels, the cylinder, the collar of the thrust bearing, the hub of the drive coupling and by a number of intermediate sleeves and sockets [4].

Fig II.7.the compressor rotor [4].

II.4.2. The shaft

The shaft consists of a central part, with a constant diameter, where the wheels and intermediate and two-end sleeves with appropriately reduced diameters where the bearings and end seals work

II.4.3. Wheels

The wheels are fretted on the shaft. Tongues having the function of transmitting the torque are provided under the wheels The negative mounting tolerance of the wheels is necessary for:

- Transmit the engine torque
- Avoid their loosening at high vibration speeds due to the stresses due to centrifugal forces
- Avoid the formation of an imbalance since the wheel would no longer be concentric with respect to the shaft. From the point of view of construction, the wheels can be of the open or closed type. The closed wheels consist of a disc, a number of blades and a counter disc. In general, the blade is tilted back

Fig. II.8.wheels [4].

II.4.4. Balancing piston

During normal operation, a thrust on the rotor develops inside the compressor, which must be absorbed by the thrust bearing. This thrust is due essentially to the distribution of the pressures acting on the wheel. It is obvious that the ΔP developed by the wheel produces a force towards the suction expressed by the product of ΔP by the surface comprised below the seal on the counter-disk. The sum of these surges is usually quite remarkable and often exceeds the capabilities of the thrust bearing.

Fig.II.9. Balancing piston [4].

II.5. MODELLING OF MECHANICAL LOSSES

Tribology is the science that studies all the phenomena that take place when bodies in contact are set in relative motion. It presents three distinct aspects

- The friction which is the resistance to an imposed displacement.
- Wear following the degradation of the surface which results in a loss of material.
- Lubrication which consists in interposing a fluid between the two bodies in contact.

It is a multidisciplinary science involving notions of mechanics, physiochemistry and materials science in general. At the beginning of the twentieth century, Tribology was based on the study of volumes, with a domination of the concepts of mechanics making it possible to establish laws of behavior. In the mid-twentieth century, Tribology turned to the study of surfaces thanks to the concepts of surface physics. For the last twenty years, Tribology research has focused on the study of the dynamics of interfaces with the awareness of the fundamental role of interfacial elements in a contact [7].

II.5.1. The friction

phenomenon of friction contributes in many usual and industrial applications. Friction is defined as resistance to movement between contacting surfaces. When two solids in contact are in motion, friction opposes the displacement forces. The latter occur at the level of the irregularities of the surfaces in contact (Figure. II.10). To mitigate them, a lubricant can be applied between the two surfaces. In all cases, it generates a resistance to movement causing the creation of superficial mechanical stresses and the dissipation of heat, thus causing the more or less rapid wear of the bodies in contact and consequently the modification of their surfaces.

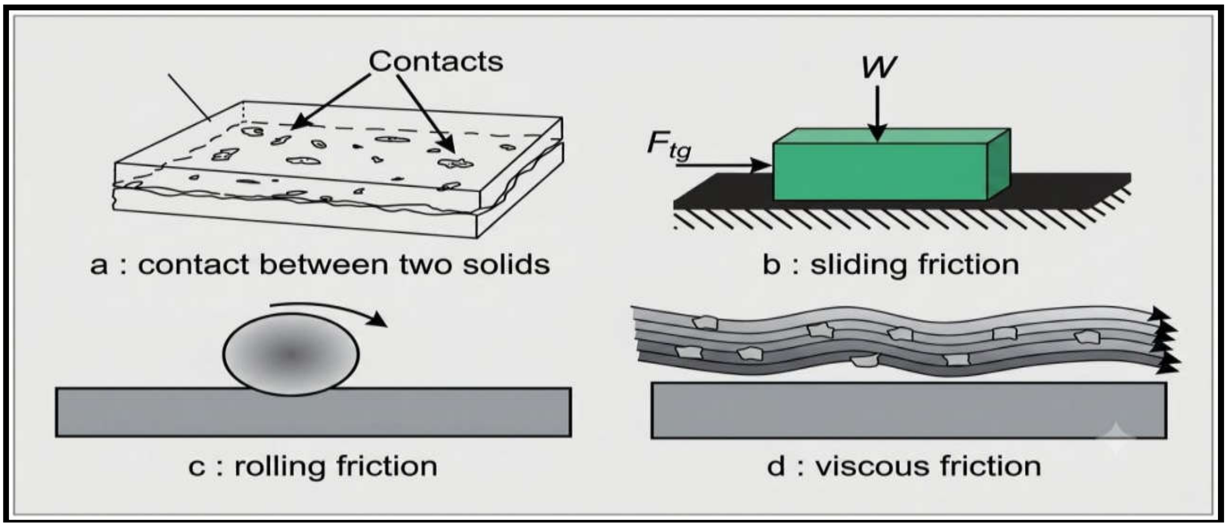

Fig.II.10. The contact interface of two moving surfaces [7].

Consequence of friction

- Loss of energy
- Overheating (risk of seizure)
- Wear

II.5.2. Lubrication principle

The principle consists in interposing between two parts in contact a body which will be able to transform a sliding (friction) into a rolling bearing. The lubricant is the basis of the bearing, with two metal parts.

II.5.3. Lubrication System (Oil Circuit)

The Lubrication system is essential for the reliable operation of radial and thrust bearings in centrifugal Compressors. It provides a continuous flow of oil that reduces friction, prevents metal-to-metal contact, and Removes heat generated during operation.

Centrifugal compressors employ two main lubrication principles:

II.5.4. Hydrodynamic Lubrication

The rotating shaft draws oil into the narrow bearing clearance, forming a pressure-generated film that supports the load and allows the shaft to rotate without direct contact with the bearing surface. This is the standard method during normal operation.

II.5.5. Hydrostatic Lubrication

Oil is externally pressurized and injected into the bearing clearance before the shaft starts moving. This ensures that the rotor is lifted on a film of oil during startup or shutdown, preventing wear.

The oil circuit typically consists of a reservoir, pumps, filters, coolers, and piping that deliver oil to both radial and thrust bearings. Proper design of this circuit is crucial for bearing longevity, thermal management, and stable compressor operation.

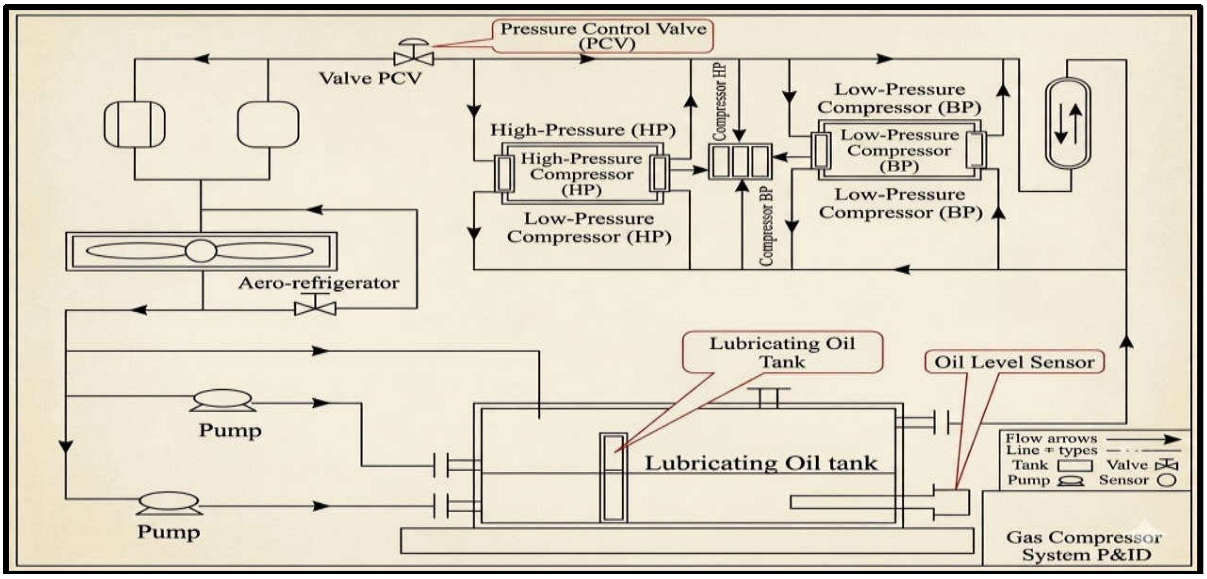

Fig. II.11. Lubrication System (Oil Circuit) [7].

II.5.6. Purpose of lubrication

- to reduce friction.
- to reduce the wear of the parts.
- How to mitigate shocks.
- how to Reduce the temperature.

- Protect from corrosion.

II.5.7. Lubrication modes

II.5.7.1. Point Lubrication

Lubricant applied before or during the movement manually or by spraying with an aerosol

II.5.7.2. Lubrification continue

The main modes of lubrication are:

- Oil lubrication by drip
- Oil-air lubrication (can replace oil mist lubrication to preserve the environment)
- Lubrication by oil bath (by bubbling)
- Lubrication by oil circulation

II.6. ADVENTAGES AND LIMITATION OF CONVENTIONAL BAERING

II. 6.1. Advantages

- **Industrial Maturity:**

Conventional bearings are based on well-established technology with decades of successful operation in turbo machinery applications. Their design principles and performance characteristics are widely documented and standardized [14].

- **High Load Capacity:**

They are capable of supporting significant radial and axial loads generated by rotor weight, aerodynamic forces, and pressure differences. This makes them suitable for high-power centrifugal compressors.

- **Vibration Damping :**

The hydrodynamic oil film provides natural damping, which improves rotor dynamic stability and reduces vibration amplitudes during high-speed operation.

- **Proven Reliability**

Due to extensive industrial use, maintenance procedures are well known, spare parts are widely available, and operational feedback has improved design reliability.

II. 6.2. Limitations

- **Complex Lubrication System:**

Conventional bearings require a complete oil circuit including pumps, filters, coolers, reservoir tanks, and instrumentation. This increases system complexity and footprint.

- **Energy Losses:**

Viscous friction within the oil film and the continuous operation of oil pumps contribute to mechanical and electrical losses, reducing overall system efficiency.

- **Environmental and Operational Risks:**

Oil leakage, contamination, and degradation may lead to environmental concerns and potential operational issues.

- **Startup and Shutdown Constraints:**

At low rotational speeds, a full hydrodynamic film may not be established, increasing the risk of wear unless hydrostatic lubrication support is provided.

II.7. Wear Mechanisms and Friction Losses in Conventional Bearings

Despite their widespread use in centrifugal compressors, conventional bearings are associated with several operational limitations that can negatively affect machine performance and reliability. The main problems encountered in these bearings can be summarized as follows:

II.7.1. Friction losses

Energy losses generated by mechanical contact between moving surfaces, leading to reduced efficiency of the compressor.

II.7.2. Wear and surface degradation

Progressive deterioration of bearing surfaces due to continuous contact and high rotational speeds.

II.7.3. Lubrication dependency

The necessity of a continuous and reliable oil lubrication system, which increases system complexity and maintenance requirements.

II.7.4. Thermal generation

Heat produced by friction that may lead to temperature rise and affect bearing life.

II.7.5. Maintenance requirements

Frequent inspection, lubrication control, and replacement operations to prevent unexpected failures.

II.7.6. Risk of oil contamination or leakage

Possible contamination of the working environment and additional operational risks.

These limitations represent significant challenges in high-speed rotating machinery such as centrifugal compressors, which has motivated the development of alternative technologies such as magnetic bearings that aim to eliminate mechanical contact and reduce friction-related losses.

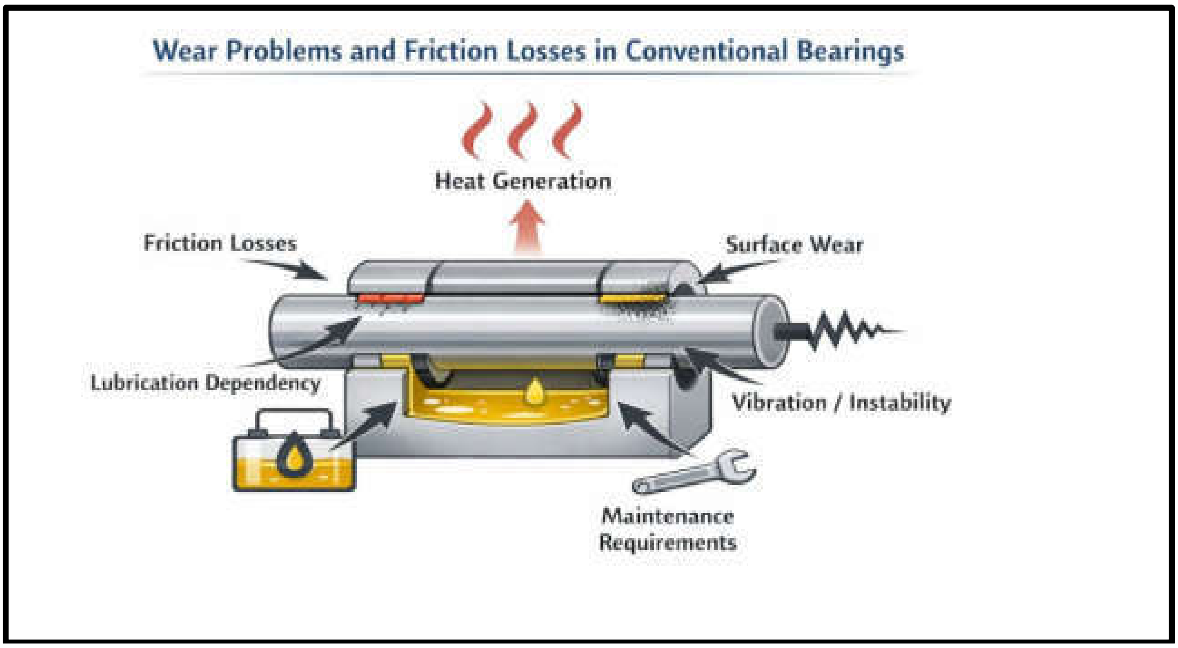

Fig.II.12. Wear Mechanisms and Friction Losses in Conventional Bearings [14].

II.8. CONCLUSION

This chapter deals with the study of centrifugal compressors equipped with conventional bearings, commonly used in the oil, gas, and energy sectors to compress fluids. They operate on the principle of a rotating wheel, the impeller, which accelerates the gas before it is converted into pressure in the diffuser. The bearings mounted on the casing provide support and guidance for the compressor's rotating shaft. They are most often of the hydrodynamic type and use a lubricating oil film to reduce friction and wear.

The analysis of these machines makes it possible to evaluate their thermodynamic and mechanical performance according to several parameters, including flow rate, pressure, temperature, and energy efficiency. Shaft vibration analysis is also essential to prevent dynamic instabilities. Due to high rotational speeds and heavy loads, bearings may undergo wear phenomena. Poor lubrication can lead to overheating and result in mechanical failures.

Rotor dynamic analysis helps to better understand the vibratory behavior of the system consisting of the rotor and the bearing. Engineers use simulation tools and software for this purpose to predict performance and detect possible anomalies. In addition, regular maintenance of the bearings extends the compressor's service life while reducing maintenance costs.

In the third chapter, our study focused on centrifugal compressors equipped with magnetic bearings, with the aim of evaluating the advantages of this innovative technology in terms of efficiency, reliability, and optimization of industrial performance.

Chapter III

Analysis of Centrifugal Compressors with Magnetic Bearings

III.1. INTRODUCTION

Active Magnetic Bearings (AMB) are widely used in rotating machinery applications due to their contactless operation and advanced motion control capabilities, offering significant advantages over conventional passive systems. Their ability to generate controllable electromagnetic forces has attracted considerable research interest. As early as 1979, Nickolajsen et al. introduced the use of AMB for vibration damping. Since then, numerous studies have focused on vibration suppression using AMB technology. These works have demonstrated that AMBs can effectively introduce adjustable stiffness and damping into the system, compensate for rotor unbalance, and significantly reduce vibration amplitudes through precise control of magnetic forces.

In industrial applications, active magnetic bearings are primarily employed to ensure the contactless levitation of the rotor, thereby eliminating mechanical friction and wear. The stable operation of machines equipped with AMB systems is achieved through accurately controlled magnetic forces generated by electromagnetic actuators. The design and implementation of such systems require multidisciplinary knowledge in mechatronics, particularly in mechanical engineering, electrical engineering, and control systems.

Despite their higher initial investment cost compared to conventional bearings, mainly due to system complexity and the need for advanced control and power electronics, AMBs offer numerous advantages. These include reduced maintenance, higher reliability, and improved operational performance. As a result, they have been successfully adopted in various industrial applications, including pumps, gas turbines, and centrifugal compressors [2-11].

III.2. GENERALITES SUR LES PALIERS MAGNETIQUES

III.2.1. History of Magnetic Bearings

The industrial development of magnetic bearings experienced a major breakthrough in 1976 with the creation of the Société de Mécanique Magnétique (S2M), resulting from a collaboration between the Société Européenne de Propulsion (SEP), based in Vernon (Eure, France), and the SKF group. However, the origins of magnetic levitation concepts date back nearly forty years earlier, reflecting a long process of technological evolution.

In the mid-1980s, the first compressors equipped with SKF–S2M magnetic bearings were commissioned. Some of these machines are still in operation today, demonstrating remarkable reliability, with no major maintenance intervention during the first 25 years of service.

Since then, more than1000 turbo machinery systems using magnetic bearings have been installed, particularly in the oil and gas industry. Many of these systems operate in some of the harshest environments in the world, ranging from the deserts of Saudi Arabia to offshore platforms in the North Sea, and the Siberian fields beyond the Arctic Circle. These performances confirm the maturity and robustness of this technology in modern industrial applications [2].

III.2.2. Definition of Magnetic Bearings

A magnetic bearing is an advanced type of bearing that uses magnetic forces to levitate and stabilize a rotating shaft without any physical contact. This contactless support is achieved through controlled magnetic fields generated by either electromagnets or permanent magnets.

By eliminating mechanical contact, magnetic bearings significantly reduce friction, wear, and the need for lubrication systems. This results in improved efficiency, higher operational speeds, and enhanced reliability compared to conventional bearing systems [10].

III.2.3. Role of Magnetic Bearings in Rotating Machinery

Magnetic bearings play a crucial role in modern rotating machinery by providing non-contact support and precise control of rotor position. They enable stable operation at high rotational speeds while minimizing vibrations and mechanical losses.

In centrifugal compressors, magnetic bearings enhance performance by eliminating friction and reducing maintenance requirements. Their ability to actively control rotor dynamics contributes to improved efficiency, reliability, and operational lifespan [11].

III.2.4. Classification of magnetic bearings

In general, magnetic bearings are divided into three main types according to the method of generating and controlling the lifting force.

III.2.4.1. Active Magnetic Bearings (AMB)

The electromagnetic Active Magnetic Bearing is a system that achieves rotor stabilization without mechanical contact by generating an electromagnetic force of attraction by an iron core and a solenoid. The system continuously monitors the location of the rotor using high-precision displacement sensors, and then transmits the resulting signals to the control unit where they are processed by various control algorithms such as PID,Fuzzy, or Sliding Mode to generate the necessary control signal for the coil, adjusting the magnetic force and ensuring that the rotor remains in its central position and stable. The stiffness and absorption of the bearing can also be adjusted by controlling the coil current. This type of bearing is characterized by its small size, reliance on an inverter motor, strong nonlinear behavior, mature and reliable technology, and is classified by the number of magnetic poles such as 8, 16, and 32 poles, where the octagonal structure is the most widely used in industrial applications [10].

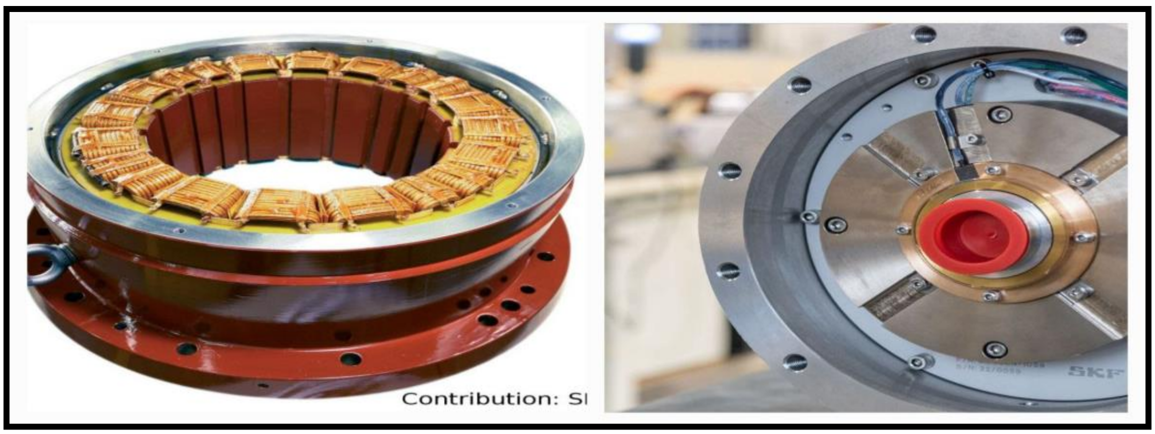

Fig.III.1. Active Magnetic Bearings**(AMB)** [16].

III.2.4.2. Passive Magnetic Bearings (PMB)

are a kind of bearings that rely on permanent magnets to generate lifting force and stabilize the rotor without the need for an active control system or an external power source. Such bearings operate on the principle of repulsion or magnetic attraction to maintain the position of the rotor, which significantly reduces friction and eliminates the need for lubrication. However, they suffer from a limitation in self-stability due to the laws of physics (such as Earnshaw's theorem), so they are often used with auxiliary systems or combined with active bearings. PMB is characterized by its simplicity, high reliability, lack of need for complex maintenance, but it is less controllable and accurate compared to active magnetic bearings [10-11].

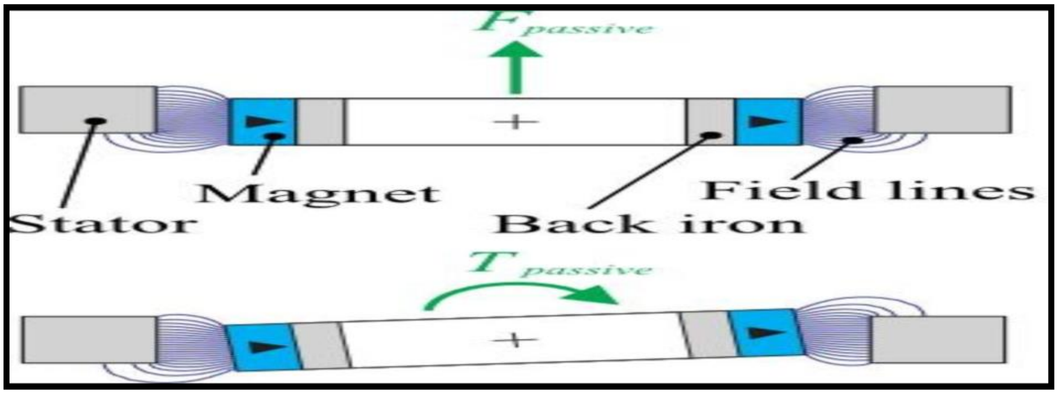

Fig.III.2. Passive Magnetic Bearings(PMB) [12].

III.2.4.3. Hybrid Magnetic Bearings (HMB)

are systems that combine Active Magnetic Bearings (AMB) and Passive Magnetic Bearings (PMB). Permanent magnets are used to provide a constant portion of the levitation force, while the active control system ensures precise stabilization of the rotor. This combination reduces energy consumption compared to fully active systems while maintaining good control performance and stability. HMB sare characterized by lower power consumption than AMBs, higher stability than PMBs, and a balanced compromise between performance and cost [11].

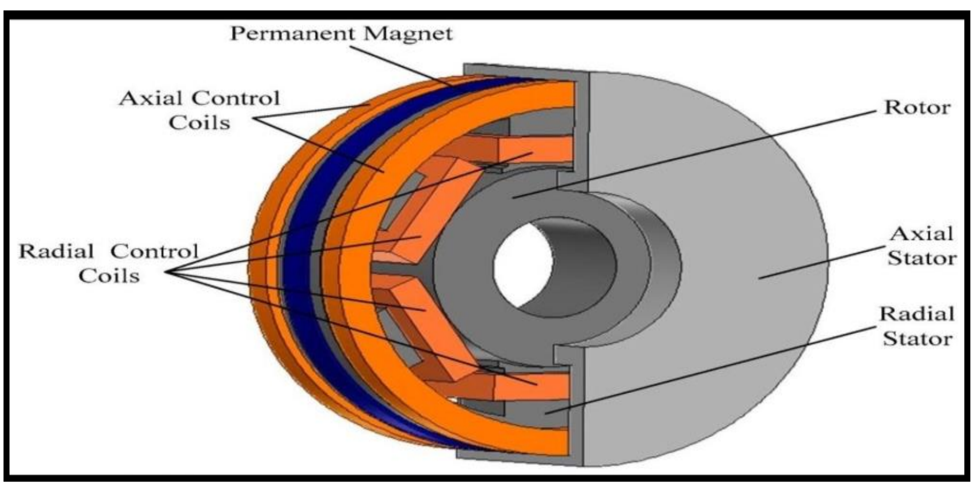

Fig.III.3. Hybrid Magnetic Bearings (HMB) [12].

III.2.5. Applications of Magnetic Bearings

Magnetic bearings are used in areas where mechanical systems reach their limits.

III.2.5.1. High-Speed Applications

the absence of contact in magnetic bearings makes it possible to achieve much higher rotational speeds. The limit is defined by the mechanical rupture of the rotor due to the centrifugal forces generated by rotation.

Mechanical suspension presents balancing problems at high speeds. It is mechanically impossible to make the axis of rotation of a bearing coincide exactly with the axis of inertia of the rotating part. As a result, even a very small unbalance can lead to significant vibrations.

The use of magnetic bearings makes it possible to overcome these balancing problems, since the axis of inertia can align with the axis of rotation [2-11].

III.2.5.2. Applications Where Friction Must Be Minimized

Friction is completely eliminated in fully magnetic suspension systems, as there is no contact between moving parts and stationary parts. However, variations in the magnetic field experienced by the rotating part can generate losses due to induced currents (eddy currents) and hysteresis.

These losses, caused by rotation, can be considered equivalent to fluid friction. On the other hand, magnetic bearings exhibit no dry friction, which eliminates all stick-slip phenomena [11].

III.2.5. 3. Applications Where Wear Must Be Minimized

Since there is no contact between the stationary and rotating parts, the service life of magnetic bearings can be considered virtually unlimited (except in the case of failure or accidental damage).

This advantage is particularly significant in systems such as satellites, where the bearings of rotating components cannot be replaced or maintained regularly. Moreover, the absence of wear is highly beneficial in specific environments, as it does not generate any particles or dust [2].

III.2.5.4. Applications Where High Precision Is Required

An active magnetic bearing, controlled by a feedback system, enables highly precise positioning of the rotating part. This precision depends primarily on the quality of the sensors used and is therefore not significantly affected by external disturbances or mechanical constraints [2].

III.2.5. 5. Applications Involving Significant Temperature Variations

A magnetic suspension system, when manufactured using appropriate materials, is capable of operating under extreme temperature conditions. It can function at very low temperatures, close to absolute zero, as well as at high temperatures, such as those encountered at the outlet of a compressor [2].

III.3. INTEGRATION OF MAGNETIC BEARINGS IN CENTRIFUGAL COMPRESSORS

III.3.1. Definition

The integration of magnetic bearings into centrifugal compressors represents a significant advancement in turbo machinery design. Unlike conventional bearing systems, magnetic bearings allow the rotor to operate without physical contact, eliminating the need for lubrication systems and reducing mechanical wear.

In centrifugal compressors, magnetic bearings are typically installed to support both radial and axial loads of the rotor. Their integration requires the inclusion of several key components, such as position sensors, control units, and power amplifiers, which work together to ensure stable and precise rotor positioning.

The design and installation of magnetic bearings must take into account various mechanical and operational constraints, including rotor dynamics, alignment, temperature effects, and system vibrations. Additionally, the control system plays a crucial role in maintaining stability, especially under varying operating conditions [11].

III.3.2. The phenomenon of magnetic levitation

Magnetic Bearings operate based on the principle of magnetic levitation, where the rotor is suspended without any mechanical contact with the stator by means of controlled electromagnetic forces. The bearing system consists of a rotor mounted on the shaft and a stator equipped with electromagnets and position sensors. These sensors continuously monitor the displacement of the rotor relative to its nominal position.

The measured position signals are transmitted to an electronic controller that processes the information and determines the corrective control action. The controller then sends commands to power amplifiers which regulate the current supplied to the electromagnets. By adjusting the electromagnetic forces in real time, the system maintains the rotor centered within a small air gap between the rotor and the stator. This closed-loop feedback mechanism ensures stable levitation, eliminates mechanical contact, and significantly reduces friction and wear in high-speed rotating machinery such as centrifugal compressors, turbines, and pumps.

They consist of three main components:

- The stator and the rotor of the bearing, which apply the electromagnetic forces causing the shaft to levitate.
- position sensors that locate the position of the shaft on 5 axes
- a controller and control algorithms, which control the current sent to the stator of the magnetic bearing and keep the shaft in a predefined position. It is because of this that the authors called the levitations using this principle: active magnetic levitations, or more often: active magnetic levitations. Active magnetic bearings (AMBs) use control systems to control the magnetic field in order to produce the call forces that act directly on the suspended body [2].

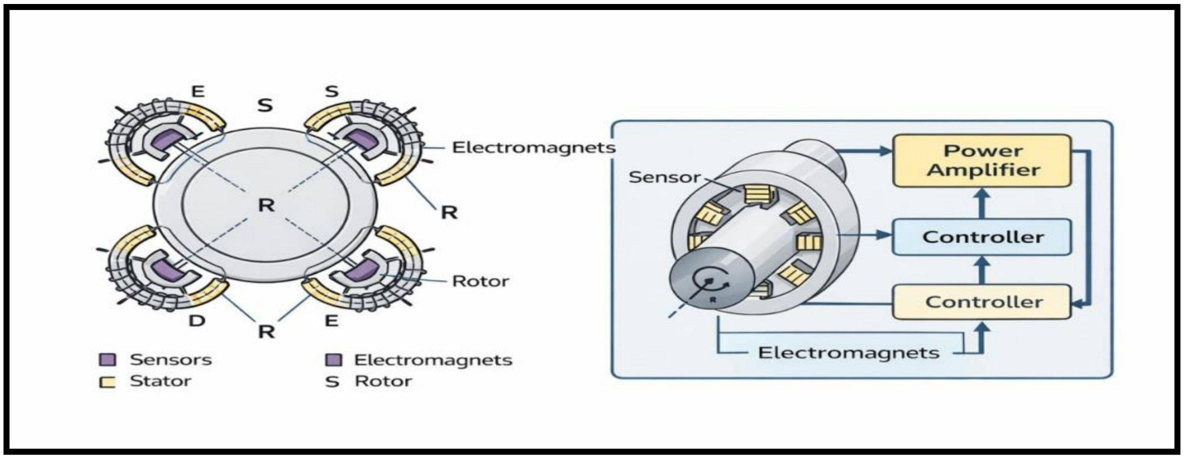

Fig.III.4. Principle of Active Magnetic Bearing Suspension [2].

III.4. ACTIVE MAGNETIC BEARING TECHNOLOGY

The active magnetic bearing (AMB) system consists of two main parts: the bearing unit and the electronic control cabinet. The bearing unit includes four main components: radial bearings with position sensors, axial (thrust) bearings with sensors, a speed sensor, and auxiliary (backup) bearings.

The radial bearing is composed of a stator and a ferromagnetic laminated rotor core maintained in position by a magnetic field. This field is generated by two pairs of opposing electromagnets mounted on the stator. The ferromagnetic laminations consist of non-oriented Fe–Si steel sheets (approximately 0.25 mm thick) assembled on the shaft. The electromagnets are made of laminated ferromagnetic steel sheets (about 0.35 mm thick), similar to those used in electric motors. An air gap of approximately 0.5 mm is maintained between the rotor and the stator.

The radial position of the rotor is monitored using inductive sensors. When the rotor deviates from its nominal position, the position sensor detects this displacement and transmits a signal to the electronic control loop. The controller then adjusts the current supplied to the electromagnets, generating corrective forces that restore the rotor to its equilibrium position.

The axial (thrust) bearing consists of a solid ferromagnetic disc mounted on the shaft. Two axial bearing stators, each made of a solid steel torus, are positioned on either side of the disc. An air gap of approximately 0.75 mm is maintained between the rotor disc and each stator. The coils are wound in annular slots to form the electromagnetic windings. Radial slots filled with laminations are used to reduce eddy current losses and enhance the dynamic response of the bearing.

The axial motion of the shaft is controlled in the same manner as the radial motion, using an axially mounted position sensor and a feedback control system.

A battery backup system is incorporated to ensure safe operation of the magnetic bearing in the event of a power failure [2].

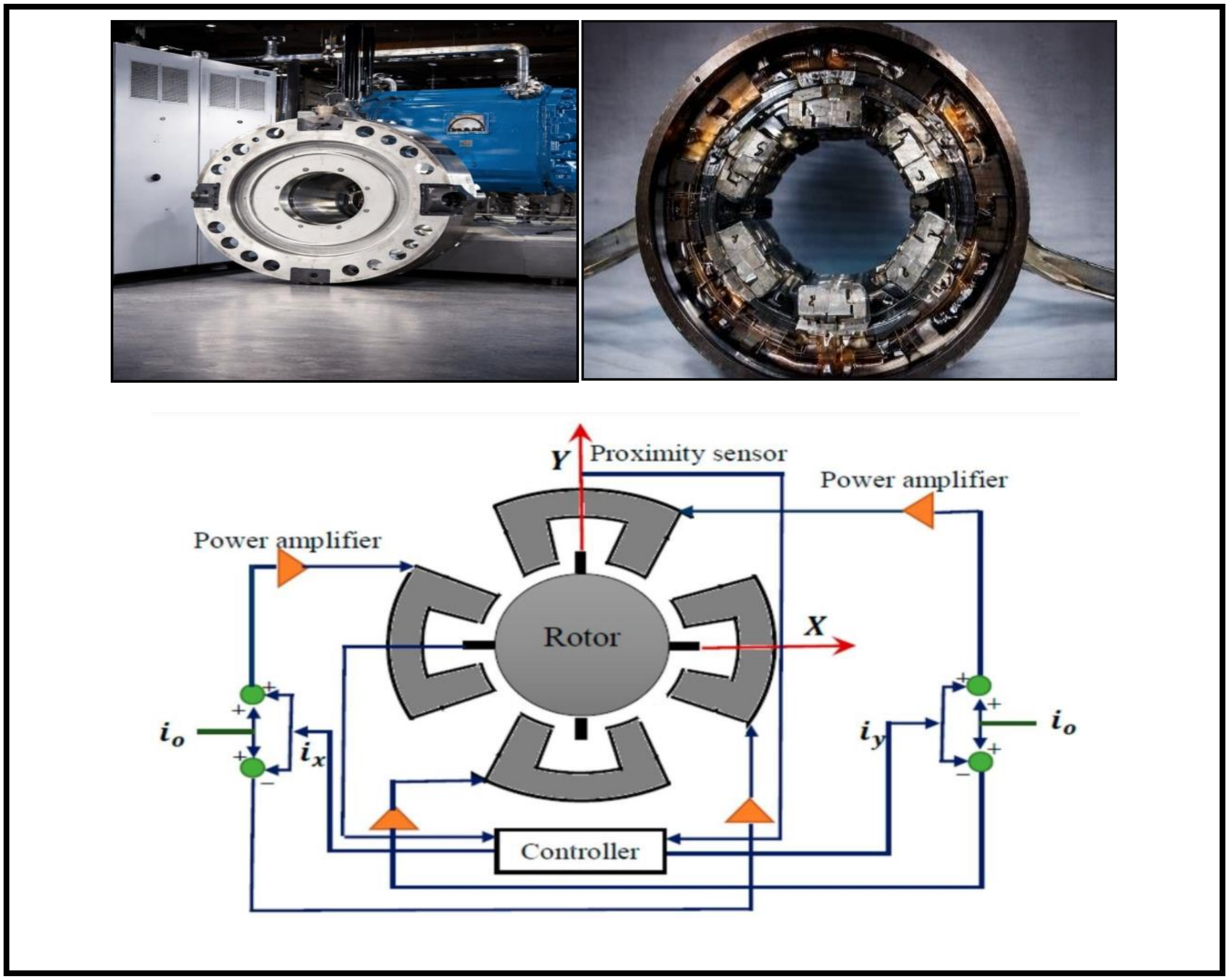

Fig.III.5. Structural components and control system schematic of Active Magnetic Bearings (AMB) [2].

III.4.1. Radial Magnetic Bearings

Since active magnetic bearings provide a contactless rotor support, the parts and components do not experience wear. Additionally, there is no need for a lubrication system, which enhances the compressor's reliability. With oil-free operation, the bearings do not suffer any mechanical losses. In the absence of a lubrication system and its related components, the power required to operate the compressor is significantly reduced [2].

Fig.III.6. Radial Magnetic Bearings [15].

III.4.2. Axial Magnetic Bearings

It is similar to a thrust bearing; it positions the rotor axially relative to the stator, based on the principle of magnetic levitation. It is capable of supporting the resultant axial forces from the balancing piston wheels and the coupling in all operating conditions of the compressor. (Figure III.7) [2].

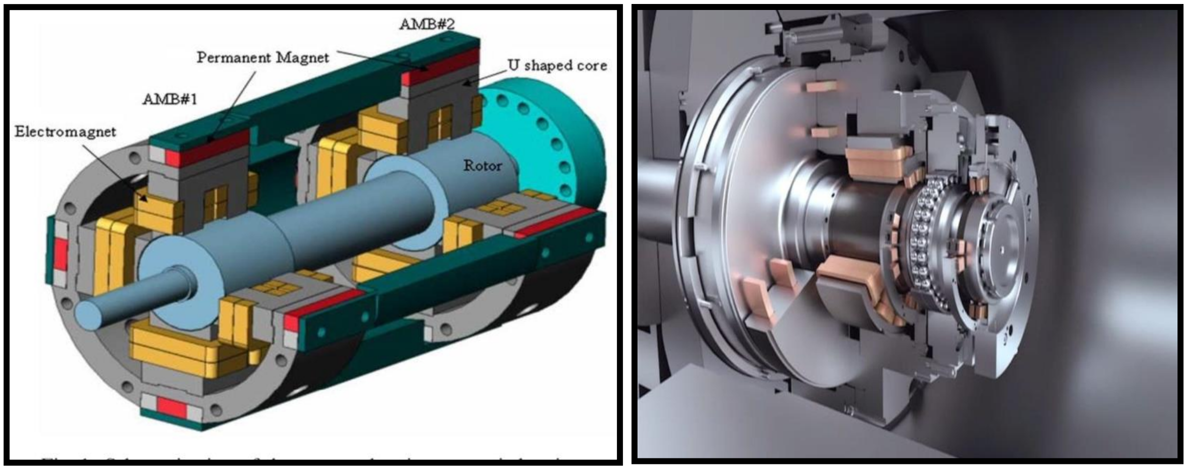

Fig.III.7. Axial Magnetic Bearings [12].

III.4.3. Auxiliary Bearing

Auxiliary bearings are made of dry-lubricated ball bearings that operate in both radial and axial planes. These bearings, located at the midpoint of the magnetic bearing gap, serve to protect the ferromagnetic sheets in the rotor and stator in case of electronic system failure. The rotor rests on the auxiliary bearings when the machine is not running [2].

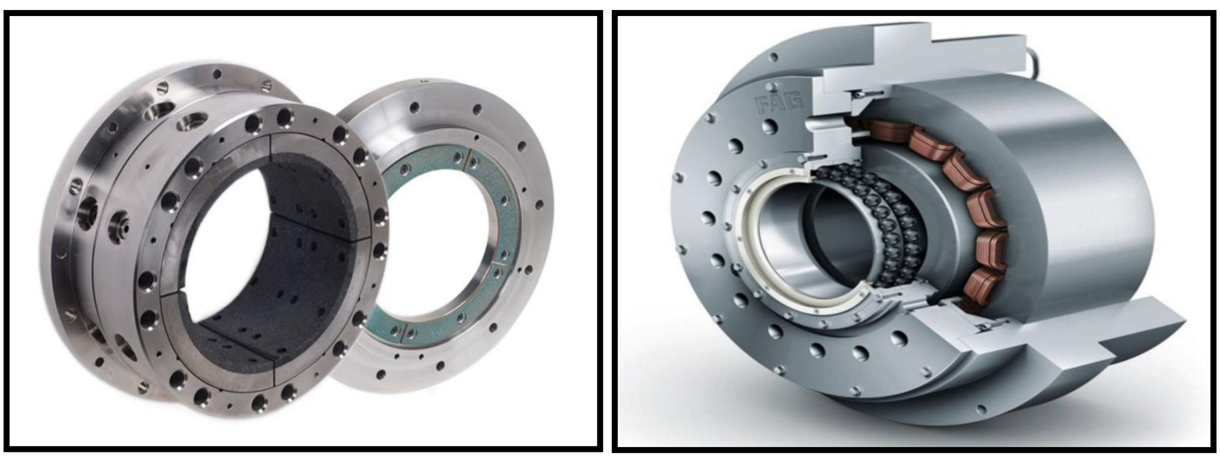

Fig.III.8. Auxiliary Bearing [13].

III.4.4. Control Cabinet

The electronic control system housed in a control cabinet maintains the rotor's position by acting on the output provided by the position sensors and then applying current to the electromagnets. The sensor signals are compared to a reference signal (the rotor's nominal position). An error signal is generated when the rotor is out of position. This is processed by the control loop, and the power amplifiers are commanded to supply more or less current to the appropriate bearing quadrant. The control electronics also include the monitoring and safety system, which can trigger alarms and shutdowns before a failure occurs.

The control system generates two types of shutdowns. A normal shutdown allows the unit to stop in a controlled manner, while an emergency shutdown requires the unit to stop as quickly as possible. Both shutdowns trigger a unit lock condition, which must be manually reset before the unit can restart.

As a next-generation control cabinet for SKF S2M Magnetic Bearings, the E300V2 is the result of expertise gained from over 1000 oil and gas installations worldwide. The new cabinet design incorporates the latest technologies developed during the creation of the subsea control cabinet used in the first-ever subsea gas compression system, now operating in the Asgard gas field off the coast of Norway. The E300V2 enables users to increase the uptime of their rotating equipment and minimize costs over the entire system lifecycle [2].

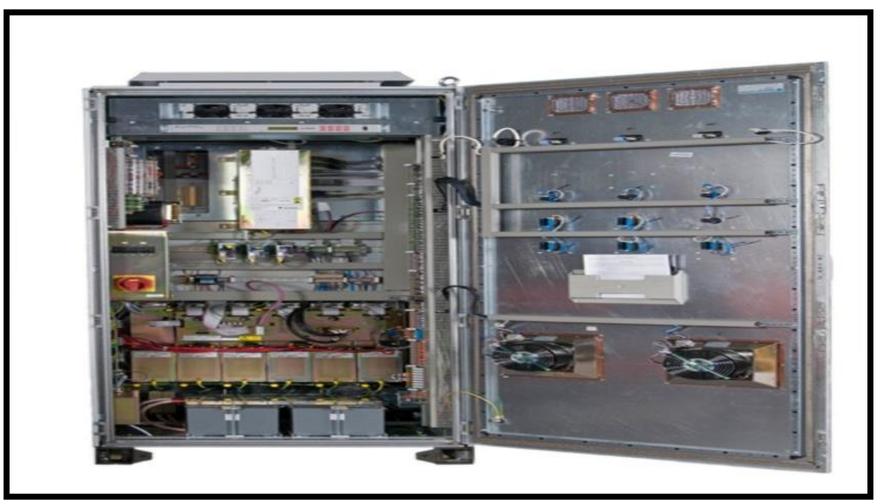

Fig.III.9. Control Cabinet [2].

III.4.5. Position Sensors

High-resolution position sensors, digital processing, and communications are integral to magnetic bearings. When connected to an external computer, features such as orbit visualization, advanced diagnostics, trend analysis, data archiving, and alarms are all possible. Health monitoring can be easily extended using additional software.

The rotor's radial position is monitored by inductive sensors. These sensors detect deviations of the rotor from its nominal position. If the rotor moves, the position sensor signals the electronic control loop, which then directs current to the electromagnet to return the rotor to its nominal position.

The axial movement of the shaft is managed in the same way as the radial movement, using a position sensor mounted axially [11].

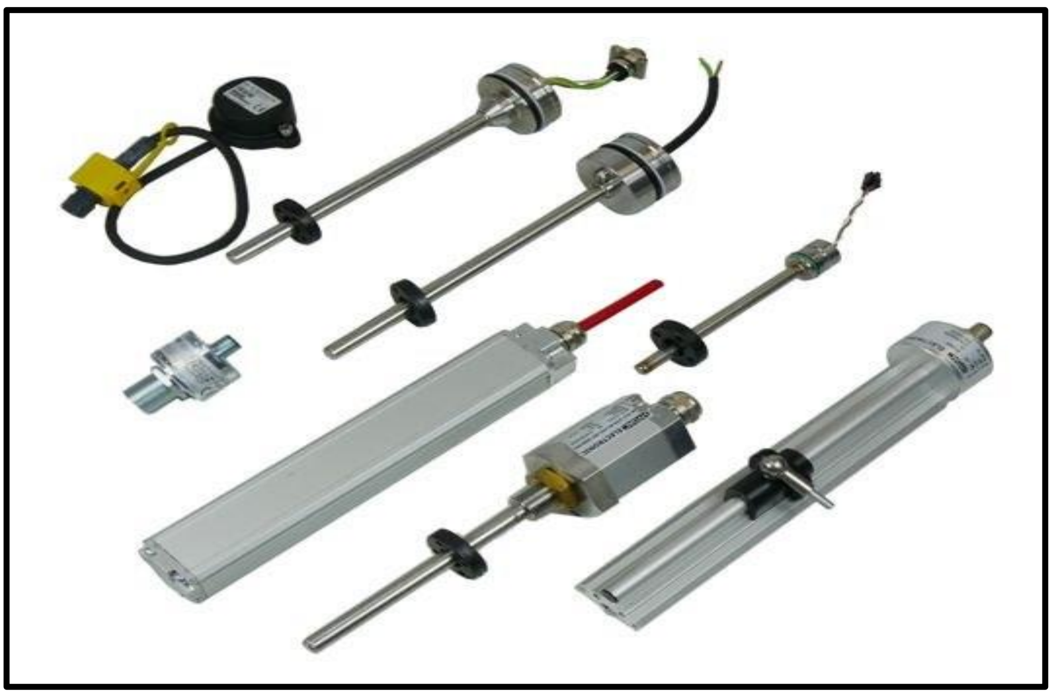

Fig. III.10. Position Sensors [16].

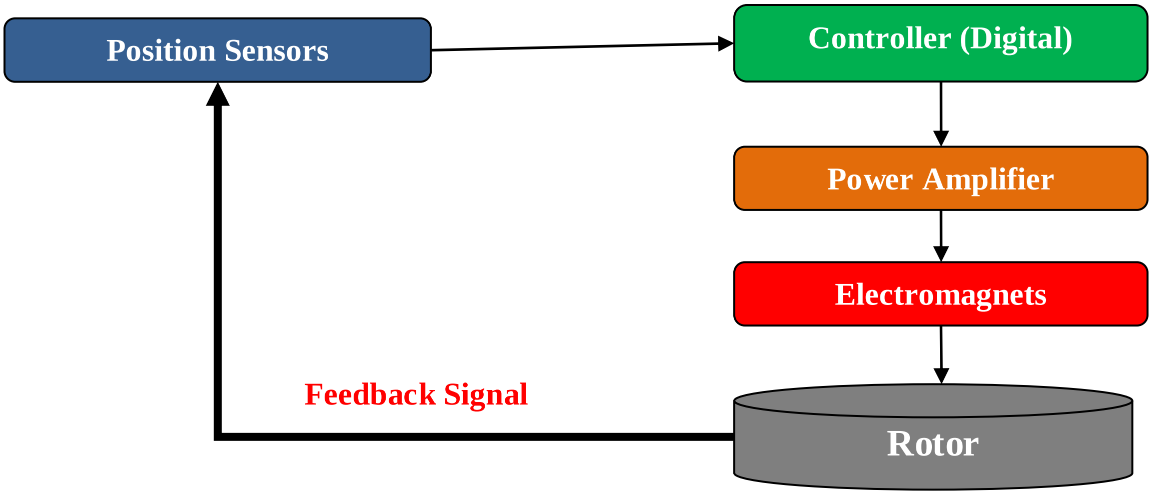

Fig.III.11. Simplified control schematic of an active magnetic bearing

III.5. SEALING SYSTEM OF MAGNETIC BEARINGS

The industry has faced similar sealing challenges, especially when working with compressors. It is essential to prevent the system pressure from escaping along the shaft.

New-Seal TM solutions enable non-contact shaft sealing for both liquids and gases. While conventional sealing technologies allow a small amount of controlled leakage, New-Seal TM technology comes much closer to achieving near-zero leakage than any other existing technology.

Magnetic bearings can operate directly in environments containing natural gas and acid gas. In some cases, they can eliminate the need for Dry Gas Seals, along with the associated issues such as seal wear, maintenance, replacement, and downtime. These technologies are notably used in systems developed by Waukesha Bearings.

Externally pressurized porous gas magnetic bearings are used in sealing applications for centrifugal compressors. This represents a new class of sealing technology offering capabilities that did not previously exist. In certain configurations, the magnetic bearing itself can ensure sealing, meaning that no additional sealing system is required [2].

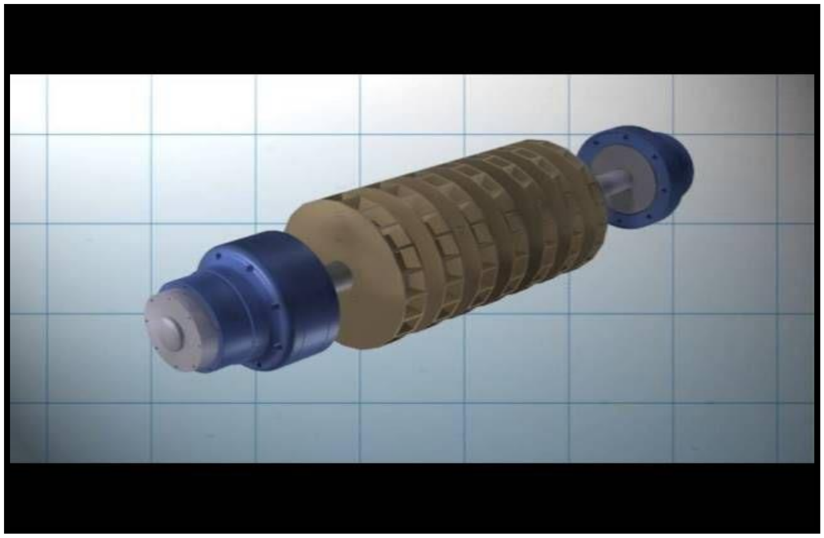

Fig.III.12.waukesha magnetic bearings [2].

The integration of magnetic bearings with the New-Seal TM system is possible. However, due to the lack of detailed information about this technology, this study focuses on Dry Gas Seals, as they are considered more reliable compared to oil-based sealing systems.

III.6.OPERATING PRINCIPLE OF MAGNETIC BEARINGS

Figure III.13 illustrates the basic configuration of a five-axis magnetic bearing system. Typically, two radial magnetic bearings support and position the shaft in the lateral (radial) directions, while one bearing supports and positions the shaft in the axial (longitudinal) direction. The magnetic bearing provides very low frictional resistance to rotation.

Each magnetic bearing consists of a rotor that rotates with the shaft and a stator containing electromagnets and position sensors. An active magnetic bearing maintains the air gap between the rotor and the stator using a closed-loop feedback control system to regulate the shaft position.

Position sensors detect small displacements, a digital processor interprets these signals, and power amplifiers supply the required current to the electromagnets. This cycle of position sensing, signal processing, and electromagnetic actuation is repeated up to 15000 times per second.

Like other types of bearings, magnetic bearings provide stiffness and damping. However, unlike conventional bearings, their performance can be optimized simply by adjusting control parameters. Advanced control algorithms help minimize machine vibrations even in the presence of significant rotor imbalance [2].

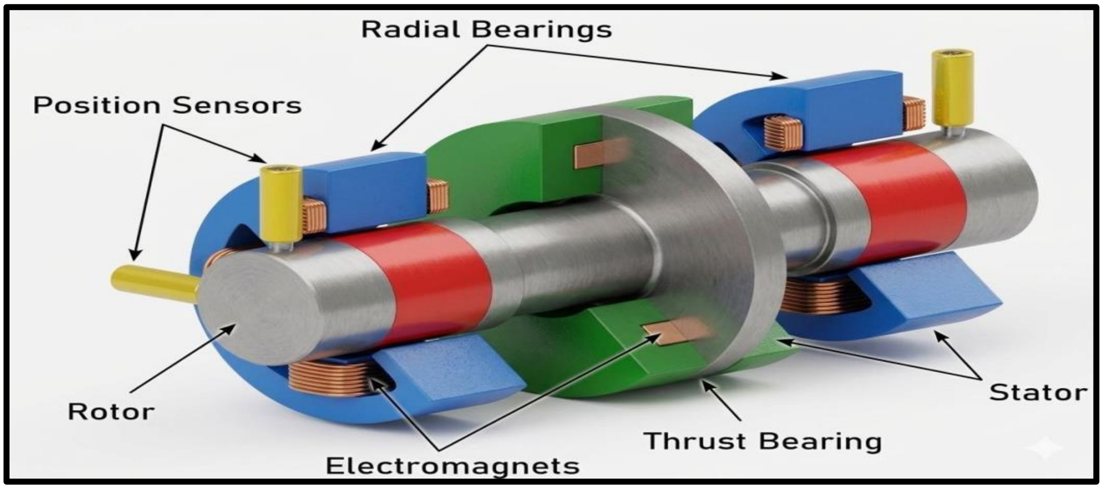

Fig.III.13. Basic operating principle of a magnetic bearing [2].

III.7. CHARACTERISTICS OF MAGNETIC BEARINGS

Magnetic bearings have several important characteristics that make them highly efficient and suitable for advanced industrial applications.

- Magnetic bearings do not require any lubricant, which eliminates the need for oil or grease systems.

- They are suitable for machines operating under vacuum conditions, cryogenic or very high temperatures, and corrosive process fluids.

- They are also used in applications where lubricant contamination is not acceptable or where wear particles must be avoided.
- Magnetic bearings are recommended when lubricants are incompatible with the process.

- The absence of lubrication systems allows the removal of pumps, filters, and other auxiliary equipment.

- This leads to a reduction in total operating and maintenance costs.

- Magnetic bearings have very low shaft rotational losses.
- This results in lower compressor power consumption and higher efficiency.
- Due to low losses, operating temperatures are generally lower than those of fluid-film bearings. This reduces the need for cooling systems [2-11].

III.8. ADVANTAGES AND LIMITATIONS OF MAGNETIC BEARINGS

III.8.1. Advantages

Magnetic bearings offer several advantages compared to conventional bearings. The most significant benefits include contactless operation, the absence of lubrication, and the elimination of wear due to contamination. As a result, the rotor can operate at very high speeds, with the maximum limit being defined only by the mechanical strength of the rotor material.

At high operating speeds, friction losses are typically 5 to 20 times lower than those of conventional journal bearings. Due to the absence of mechanical wear, magnetic bearings provide a longer service life and reduced maintenance requirements [10].

Another major advantage is the reduction of parasitic power losses. In compressor applications, magnetic bearing systems consume significantly less energy compared to conventional lubrication systems, mainly due to the elimination of oil shear losses and auxiliary equipment such as pumps and cooling fans.

Maintenance is also simplified, as there is no need for lubrication systems, eliminating issues related to oil contamination and reducing operational complexity. This leads to improved system reliability and extended Mean Time Between Failures (MTBF) [11].

Magnetic bearings contribute to system compactness, allowing a reduction in size and weight compared to traditional bearing systems. This is particularly beneficial in applications where space optimization is critical. In addition, magnetic bearings improve rotor dynamic stability. They allow the rotor to rotate around its inertial axis rather than its geometric axis. Undesirable vibration frequencies can be mitigated through electronic control, enabling smooth and stable operation.

Furthermore, the integrated monitoring capability of magnetic bearings provides valuable diagnostic information. It enables real-time detection of rotor imbalance and facilitates condition monitoring and performance optimization.

Finally, magnetic bearings enhance system stability under demanding operating conditions, such as near surge limits in compressors. They actively compensate for fluctuating radial forces, maintaining the rotor centered and minimizing orbital motion [2].

III.8.2. Limitations

Despite their numerous advantages, magnetic bearings also present several limitations that must be considered in industrial applications.

of the main drawbacks is the high initial cost associated with their design, manufacturing, and installation. This is mainly due to the complexity of the system, which includes sensors, controllers, power electronics, and electromagnetic actuators.

Magnetic bearings rely heavily on an active control system to ensure stable operation. Therefore, any failure in the control electronics, sensors, or power supply can lead to system instability or shutdown. For this reason, additional safety components such as backup bearings and battery systems are required, which increases system complexity.

Another limitation is the continuous energy consumption required to maintain the magnetic field, particularly in active magnetic bearings. Unlike conventional bearings, which may operate passively, AMBs require a constant power supply.

Furthermore, the design and implementation of magnetic bearing systems require advanced expertise in mechatronics, including mechanical engineering, electrical engineering, and control systems. This increases the difficulty of installation, operation, and maintenance.

Magnetic bearings can also be sensitive to external disturbances, such as electromagnetic interference or sudden dynamic loads, which may affect system performance if not properly controlled.

Finally, although maintenance is reduced compared to conventional systems, the need for specialized monitoring and control equipment introduces additional operational constraints [2-11-13].

III.9. ADAPTATION OF MAGNETIC BEARINGS TO CENTRIFUGL COMPRESSORS

The active magnetic bearing (AMB) system integrated into centrifugal compressors is generally similar in configuration to conventional bearing systems, which typically include two radial bearings and one axial (thrust) bearing. Each bearing is designed to support both the static and dynamic loads of the compressor rotor.

In addition, appropriately sized auxiliary (backup) bearings are installed outside the magnetic bearings to ensure system safety and facilitate maintenance when required. Position sensors are also arranged in a similar manner to those used in conventional systems [2].

III.9.1. Adaptation of Dry Gas Seals to Magnetic Bearings (Case Study)

In industrial applications, such as centrifugal compressors operating in the (HRM) region, the integration of AMBs requires specific modifications to the dry gas sealing system, while preserving the overall compressor design. In most cases, no major changes are required to the casing or the aerodynamic configuration of the compressor.

To ensure compatibility with magnetic bearings, conventional contact-based sealing elements, such as carbon bushings and lip seals, are replaced with non-contact labyrinth seals. A multi-stage sealing arrangement is implemented, where the first stage provides the primary pressure drop, and the second stage acts as a backup to ensure safe operation in case of failure.

Additional venting ports are introduced to evacuate leakage gases and prevent their accumulation within the system. Leakage from the first stage is monitored using the existing dry gas seal monitoring system, while leakage from the second stage remains negligible.

To further enhance protection, a controlled air purge system is implemented to maintain a positive pressure inside the bearing housing. This prevents process gas from entering the magnetic bearing cavity and protects sensitive components from contamination and electrical failure.

Modifications are also made to the seal housing by adding additional venting passages and O-ring seals to ensure proper separation between sealing stages. Furthermore, the lubrication system is partially modified by removing unnecessary oil piping associated with conventional bearings, while maintaining lubrication only for auxiliary systems such as gas turbine bearings.

Finally, additional vent lines are installed at both ends of the compressor to safely discharge gas leakage and air–gas mixtures to the external environment, ensuring safe and reliable operation of the system [2].

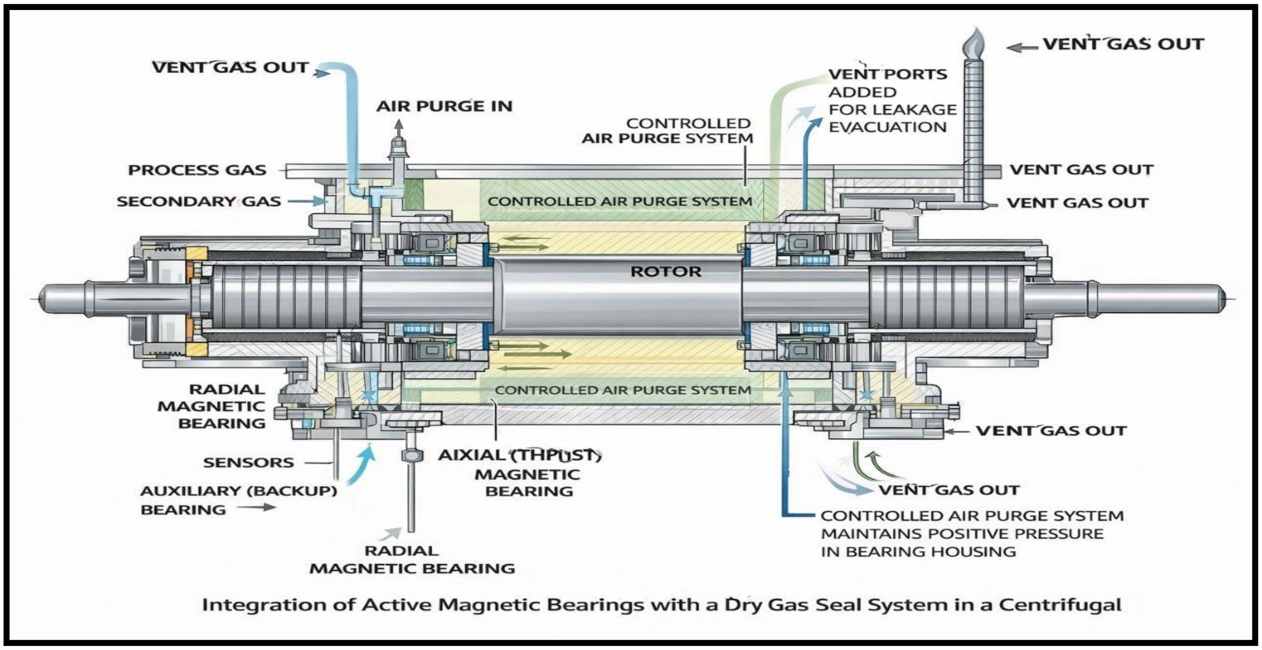

Fig.III.14. Adaptation of the Gas Seal to Magnetic Bearings in Centrifugal Compressors [2].

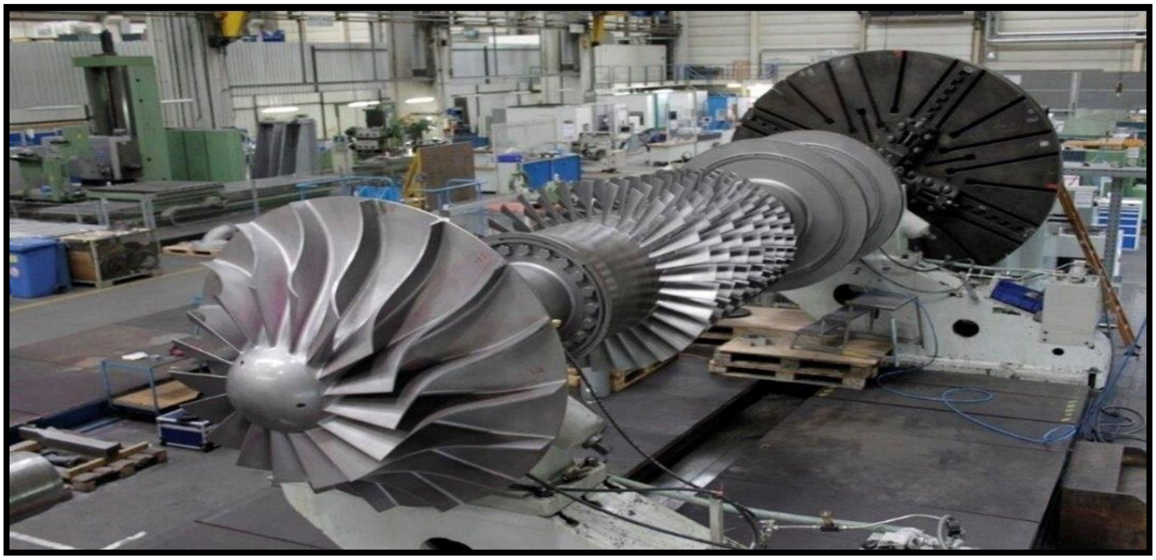

Fig.III.15. Industrial View of a Centrifugal Compressor Rotor Supported by Magnetic Bearings [3].

III.10. TECHNOLOGICAL STUDY OF MAGNETIC BEARINGS

III.10.1. Speed and Acceleration Limits

Magnetic bearings do not limit the speed or acceleration of the components they support. Systems operating at 20,000 rpm or more have been developed for special applications such as centrifugal compressors.

III.10.2.Resolution

Since there is no friction in magnetic bearings, the motion resolution of the rotor is limited only by the actuator, the sensor, and the control system used.

Magnetic bearings are effective only in attraction mode. In order to achieve high performance in systems with randomly oriented force components, magnetic bearings should be used in an opposed-mode design [2].

III.10.3. Vibration and shock resistance

- **Vibration control:** A closed-loop control system of a magnetic bearing can be used in conjunction with accelerometer feedback to generate forces opposite to those created by vibration. The net effect is the cancellation of vibration. Vibrations can be reduced by up to 20 dB using this type of system.

- **Alignment:** Proper alignment between rotating components is often sufficient to significantly minimize vibrations.

- **Dynamic balancing:** Magnetic bearings can be used for in-situ dynamic balancing of components. Rotor speed, angular position, and displacement measurement data can be collected and used to determine rotor balance.

III.10.4. Environmental sensitivity

As long as the coils are protected (e.g., hermetically sealed), magnetic bearings can operate in virtually any environment. They have been successfully used in the following conditions: temperatures ranging from[-235 to 450°C], pressures from 10^{-7} torr to 8.5 MPa, and in gases such as hydrogen, methane, and nitrogen.

It must be ensured that in a corrosive environment, the system materials are capable of maintaining their structural and sealing functions [2].

III.10.5. Sealing capacity

In a normal environment, it is not really necessary to seal magnetic bearings; however, it is recommended to protect the auxiliary bearings against any risk of contamination.

III.10.6. Maintenance requirements

Magnetic bearings require virtually no maintenance. This makes them particularly suitable for equipment that must operate continuously, such as centrifugal compressors.

III.10.7. Required lifetime

Since magnetic bearings are contactless devices, they can have an essentially infinite lifespan.

III.11. CONCLUSION

The chapter devoted to the analysis of centrifugal compressors equipped with magnetic bearings highlights the major technological advances provided by this contactless suspension solution. Magnetic bearings support the rotor through electromagnetic forces, thereby eliminating any direct contact between moving components, unlike conventional bearings. This characteristic significantly reduces friction phenomena and the associated mechanical losses, thus improving the overall energy efficiency of the compressor [10-11].

The study also demonstrates that the absence of mechanical contact eliminates the need for complex lubrication systems, thereby reducing maintenance costs and minimizing the risk of contamination of compressed fluids. Furthermore, centrifugal compressors equipped with magnetic bearings provide better dynamic stability during high-speed operation, enabling more precise, quieter, and more efficient performance [10].

In addition, the integration of advanced electronic control and monitoring systems makes it possible to continuously track the dynamic behavior of the rotor. These systems can immediately detect and correct imbalances and vibrations, which greatly improves operational reliability and extends equipment service life. However, although this technology offers considerable advantages, it requires a relatively high initial investment as well as sophisticated control infrastructure, which may constitute an economic constraint for certain industrial applications.

In the fourth chapter, our study focused on a comparative techno-economic analysis between the conventional BCL 406 A centrifugal compressor used in the TFT region and the compression system consisting of magnetic bearings and dry gas seals, the latter being implemented in the Hassi R'Mel gas field operated by SONATRACH.

Chapter IV

Techno-Economic Analysis of Centrifugal Compressors: A Comparative Study between the Oil Sealing System of the BCL 406-A Type and an Alternative System Integrating Magnetic Bearings and Dry Gas Seals

IV.1. INTRODUCTION

Centrifugal compressors play a crucial role in the oil and gas industry, particularly in gas compression, transportation, and processing operations. The overall performance, operational reliability, and operating costs of these machines largely depend on the design and selection of auxiliary systems, especially bearing arrangements and sealing technologies. These subsystems constitute essential components, as they directly influence mechanical losses, maintenance requirements, and the overall efficiency of industrial installations.

Traditional centrifugal compressor configurations generally rely on oil-lubricated bearings combined with oil sealing systems. Although this technology is mature and widely implemented in industrial facilities, it requires the integration of mechanical contact components, complex lubrication systems, and additional auxiliary equipment. Consequently, such systems may lead to increased energy losses, higher maintenance demands, and various operational constraints.

At the same time, recent technological advancements have enabled the development of alternative configurations incorporating active magnetic bearings and dry gas seals. These technologies operate without direct mechanical contact and do not require oil lubrication, thereby contributing to the reduction of friction losses, the improvement of energy efficiency, and the minimization of maintenance interventions. As a result, they represent a promising solution for enhancing compression systems in the modern industrial sector.

This chapter presents a comparative techno-economic study of two centrifugal compressor configurations used for the same gas compression application. The first configuration concerns a conventional BCL 406-A centrifugal compressor equipped with oil sealing system and operating at the TFT site in Illizi. The second configuration concerns a compressor equipped with magnetic bearings and dry gas seals, operating at the Hassi R’Mel site. Both systems are used in Sonatrach facilities [18-2].

The objective of this study is to evaluate and compare the technical performance, energy consumption, reliability, and economic viability of these two configurations. Each system is examined separately, followed by a comparative analysis based on various key performance indicators such as efficiency, maintenance requirements, and total cost of ownership.

This comparison is of major interest in the context of optimizing industrial compression systems and supporting decision-making regarding the selection of the most suitable technologies for real operating conditions. The methodological approach adopted is based on the analysis of concrete operational data, thereby ensuring the validity, consistency, and robustness of the results obtained.

IV.2. GENERAL CONSIDERATIONS

IV.2.1. Maintenance

IV.2.1.1. Definition of maintenance

Maintenance can be defined as the set of actions aimed at maintaining or restoring a system, equipment, or device to a specified operational condition. It includes various activities such as troubleshooting, lubrication, repair, and improvement, all intended to preserve the functional performance of the equipment and ensure continuity of operation.

In industrial applications, maintenance plays a crucial role in sustaining production and preventing unexpected failures. Its effectiveness is not only measured by the ability to maintain system performance, but also by achieving this objective at an optimal overall cost. Therefore, maintenance quality is closely related to both technical efficiency and economic performance [3].

IV.2.1.2. Maintenance Objectives

The objectives of maintenance can be broadly classified into two main categories: financial objectives and operational objectives [4].

- **Financial Objectives**

From an economic perspective, maintenance aims to minimize the overall maintenance costs while ensuring that all required activities are carried out within a predefined budget. Achieving cost efficiency without compromising system performance is a key objective in industrial maintenance strategies.

- **Operational Objectives**

From an operational standpoint, maintenance is intended to ensure that equipment operates under optimal conditions. This includes maintaining a high level of availability, extending the service life of equipment, and ensuring safe and reliable operation at all times.

In addition, maintenance activities aim to improve equipment performance, optimize operational efficiency, and ensure that interventions are carried out only when necessary, following predefined maintenance intervals. This approach helps balance performance, reliability, and cost-effectiveness in industrial systems [6].

IV.2.1.3. Types of Maintenance

During the operation of centrifugal compressors, various components are subjected to wear, degradation, and performance deterioration over time. These effects require continuous monitoring and the implementation of different maintenance strategies to ensure proper system operation.

Depending on the condition of the equipment and operational requirements, maintenance can be classified into several types, . Each type plays a specific role in maintaining system performance, reducing the risk of failure, and ensuring operational continuity [4].

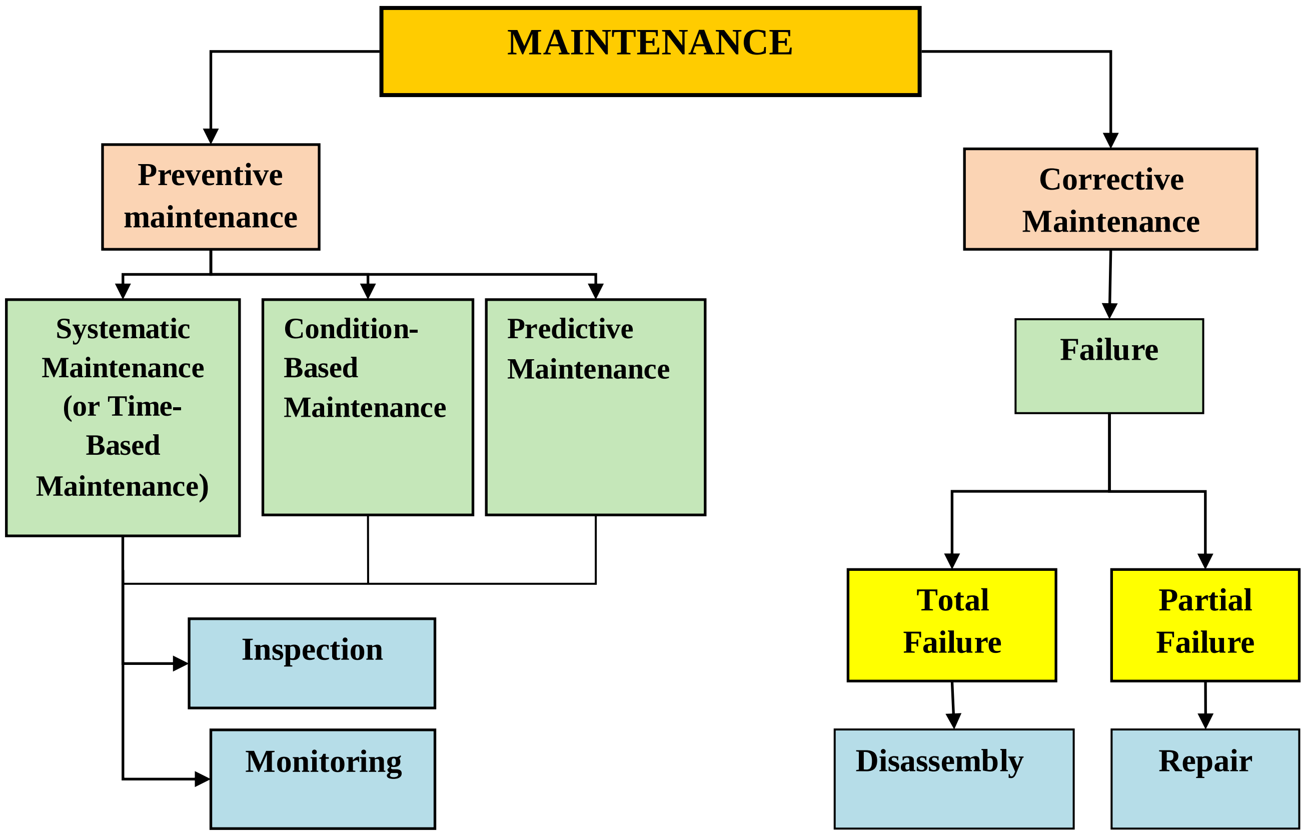

Fig.IV.1. Classification of Maintenance Types

The main types of maintenance illustrated in **(**FigureIV.1.) can be briefly defined as follows:

• **Preventive Maintenance:** Maintenance performed before the occurrence of failures in order to reduce the risk of breakdown and ensure continuous operation.

- **Systematic Maintenance:** Maintenance carried out at predefined time intervals, regardless of the equipment condition.

- **Condition-Based Maintenance:** Maintenance based on the actual condition of the equipment, monitored through inspections and measurements.

- Predictive Maintenance: Maintenance based on data analysis and monitoring techniques to predict failures before they occur [6].

- **Corrective Maintenance:** Maintenance performed after a failure has occurred to restore the system to its normal operating condition.

- Inspection: Routine checks carried out to assess the condition of the equipment and detect potential issues at an early stage.

- Monitoring: Continuous observation of system parameters to track performance and detect abnormal behavior.

- Repair: Action taken to fix a partially failed component and restore its function.

- Disassembly: Intervention required in case of major failure, involving dismantling of equipment components [6].

IV.2.2. Reliability

Reliability refers to the ability of a system or equipment to perform its intended function under specified operating conditions for a given period of time without failure. It is a key indicator of system performance, particularly in industrial applications where continuous operation is required.

In centrifugal compressors, reliability is closely related to the frequency of failures and the stability of operation.A highly reliable system operates with minimal interruptions, ensuring consistent performance and reducing the risk of unexpected shutdowns, Reliability can be expressed using the following form:

$$MTBF = \frac{T}{N} \qquad \text{(IV.1)}$$

MTBF: Mean Time Between Failures (average time between two consecutive failures), expressed in hours.

- **N:**Number of failures
- **T:**Total operating time, expressed in hours.

- The objective of this section is to define reliability as a key indicator for evaluating system performance and failure frequency.

IV.2.3. Availability

Availability refers to the proportion of time during which a system is operational and capable of performing its intended function. It reflects the combined effect of reliability and maintenance on system performance. Availability is commonly expressed as :

$$A = \frac{MTBF}{MTBF+MTTR} \quad \text{(IV.2)}$$

- **MTBF:** Mean Time Between Failures ,expressed in hours.

- **MTTR:** Mean Time To Repair, expressed in hours.

A higher availability indicates that the system is operational for a larger portion of time. Availability is a key parameter in industrial applications, as it directly impacts production continuity and overall system performance.

• The objective of this section is to present availability as a measure of the operational readiness of the system, combining reliability and maintenance performance.

IV.2.4.Maintainability

Maintainability refers to the ability of a system to be restored to its normal operating condition within a given period of time after a failure. It reflects the ease and speed of maintenance interventions, Maintainability is commonly evaluated using the Mean Time To Repair (MTTR), defined as:

$$MTTR = \frac{Tr}{N} \quad \text{(IV.3)}$$

- **Tr** : Total repair time, expressed in hours.

- **N**: Number of failures

A lower MTTR indicates better maintainability, as the system can be restored more quickly. Improving maintainability contributes to reducing downtime and increasing system availability, making it an important parameter in the evaluation of compressor systems.

• The objective of this section is to introduce maintainability as a key parameter used to evaluate the ease and speed of restoring the compressor system after a failure.

IV.2.5. Capital Expenditure (CAPEX)

Capital Expenditure (CAPEX) refers to the initial investment required for the acquisition and installation of a compressor system. It includes the cost of equipment, installation, and associated infrastructure ,CAPEX can be expressed as:

$$CAPEX = C_{equipment} + C_{installation} + C_{infrastruchure} \quad \text{(IV.4)}$$

- **C_(equipment):** Cost of the compressor and main components.

- **C_(installation):** Installation and commissioning cost.

- **C_(infrastructure):** Supporting systems and facilities

Although CAPEX is incurred only once at the beginning of the project, it plays a crucial role in the economic evaluation of different compressor technologies.

• The objective of this section is to define the initial investment cost required for compressor systems and its role in economic evaluation.

IV.2.6. Operational Expenditure (OPEX)

Operational Expenditure (OPEX) refers to the costs associated with the day-to-day operation of a compressor system. These costs are incurred continuously during the operation of the equipment.

OPEX mainly includes energy consumption, maintenance costs, and other operational expenses such as labor and auxiliary systems. It can be expressed as:

$$OPEX = C_{energy} + C_{maintenance} + C_{operation} \quad \text{(IV.5)}$$

- C_(energy): Energy cost.

- C_(maintenance): Maintenance cost.

- C_(operation): Other operational costs.

The energy cost can be estimated using:

$$C_{energy} = P \times H \times Ce \quad \text{(IV.6)}$$

- P: Power consumption

- H: Operating hours

- Ce : Energy cost per unit

Reducing OPEX is essential for improving the economic performance of compressor systems, especially in continuous industrial operations.

• The objective of this section is to describe the operational costs associated with compressor systems and their impact on long-term performance.

IV.2.7.Total Cost of Ownership (TCO)

The Total Cost of Ownership (TCO) represents the overall cost of a compressor system throughout its entire lifecycle. It includes both the initial investment and the operational costs incurred during the system's lifetime. TCO can be expressed as:

$$TCO = CAPEX + OPEX \quad \text{(IV.7)}$$

• The objective of this section is to introduce the Total Cost of Ownership (TCO) as a comprehensive indicator used to evaluate the overall cost of the compressor system throughout its lifecycle, including both investment and operational costs.

IV.3. COMPARISON BETWEEN THE OIL SEALING SYSTEM OF THE BCL 406-A MODEL AND AN ALTERNATIVE SYSTEM INCORPORATING MAGNETIC BEARINGS AND DRY GAS SEALS

IV.3.1. Study of the Oil Sealing System of the BCL 406-A Model

The analyzed compressor corresponds to a conventional centrifugal model of type BCL 406-A installed at the TFT site and operated by SONATRACH Designed by Nuovo Pignone this compressor is intended to ensure gas compression in industrial applications requiring continuous operation under variable process conditions.

The main function of this equipment is to increase gas pressure through a two-stage compression system. During the first stage, the gas pressure is raised from approximately seven bar to thirty bar [18]. Following an intermediate treatment or separation phase, the gas undergoes a second compression stage, during which the pressure increases from 30 bar to approximately 80 bar [18]. This configuration enables the attainment of the pressures required for downstream processing as well as gas transportation.

The compressor includes oil-lubricated bearings as well as an oil sealing system, both of which are essential elements for ensuring the stability and optimal operation of the rotating components. However, the presence of mechanical contacts and auxiliary lubrication systems increases the complexity of the installation, which may, in the long term, lead to higher maintenance requirements as well as increased operational constraints.

Table IV.1.Technical Characteristics of the BCL 406-A Compressor [18].

Parameter	Value
Compressor Type	BCL 406-A
Manufacturer	Nuovo Pignone
Location	TFT – Illizi
Application	Gas Compression
Suction Pressure	07 bar
Discharge Pressure (Stage 1)	30 bar
Discharge Pressure (Stage 2)	80 bar
Lubrication System	Oil-based
Sealing System	Oil sealing
Flow Rate	3,900,000 Nm³/day
Operating Hours	8000 h/year
Number of Failures	3 failures/year
Operating Cycle	3 years (22 000 h)

IV.3.1.1.Techno-Economic Assessment

This section presents the technical and economic study of the conventional centrifugal compressor BCL 406-A, installed at the TFT gas processing station in Illizi. The study aims to evaluate the compressor’s operational performance under real industrial conditions, while simultaneously integrating technical and economic indicators within a defined operating cycle.

The analysis focuses on key performance indicators, particularly reliability, maintainability, and availability, as well as the associated economic costs, including energy consumption, maintenance operations, and production losses during shutdowns.

The objective is to develop a comprehensive understanding of the compressor’s operation by correlating its technical performance with its economic impacts. This integrated methodology highlights the key factors affecting system performance, including failure frequency, repair duration, and maintenance requirements,Based on this overall assessment, the following subsection provides an in-depth analysis of maintenance, focusing on failure behavior, mean time to repair

(MTTR), and the structure of associated costs, in order to quantify the contribution of maintenance to the overall system performance and cost.

IV.3.1.1.1. Analysis of Maintenance Performance

The maintenance of a traditional centrifugal compressor largely depends on the presence of an oil-based lubrication and sealing system. This configuration requires continuous monitoring as well as periodic maintenance operations to ensure optimal equipment performance.

Preventive maintenance is a key pillar of this strategy. It includes routine inspections, oil replacement, filter servicing, and operational testing of the various subsystems. The main objective of these interventions is to reduce the likelihood of failure and to ensure long-term performance stability.

However, due to mechanical interactions between rotating components, wear is unavoidable, thereby necessitating corrective maintenance. In this context, malfunctions are likely to affect primarily bearings, sealing elements, as well as auxiliary equipment such as pumps and cooling systems.

Moreover, the complexity of the oil circuit leads to an increased maintenance workload and a higher frequency of interventions. Consequently, the conventional compressor requires relatively frequent maintenance operations, which directly impacts operating costs and overall system availability.

The maintenance cost of a compressor is estimated by taking into account both routine maintenance activities and scheduled overhauls performed throughout its lifecycle. In the case under consideration, the compressor operates over a three-year period, corresponding to approximately 22000operating hours [18].

Throughout this cycle, the implemented maintenance strategy includes two partial inspections carried out at defined intervals, as well as a major inspection performed at the end of the operating period. In addition to these major interventions, the total cost also includes preventive and corrective maintenance, spare parts, and labor costs. To determine a representative annual cost, all expenses incurred over the 03-year period are aggregated and then divided by the corresponding duration. This approach ensures a consistent evaluation of maintenance costs while accurately reflecting the operating conditions of a conventional centrifugal compressor [18].

Table IV.2.Compressor maintenance costs over a three-year operating cycle

Cost Component	Value (DZD/03year)
Preventive Maintenance	**520000000**
Corrective Maintenance	**12 600**
Lubrication Oil	**277 142670**
Spare Parts	**4 393 382**
Overhaul (annualized)	**6 258 677**
Total Maintenance Cost	**807 807 329**

The study of maintenance costs over a three-year operating period highlights the significant role of lubricating oil in the total maintenance cost of the compressor. The results indicate that this item represents the largest share of the costs, followed by overhaul operations and spare parts.

The substantial proportion of lubrication-related costs is primarily due to the requirement for a continuous oil supply in conventional compressors, in order to ensure proper lubrication and sealing functions. Furthermore, periodic overhaul operations, including both partial and major maintenance interventions, also account for a significant share of the total maintenance cost.

Expenditures related to preventive and corrective maintenance remain relatively modest compared to other cost items; however, they constitute a fundamental element in ensuring the reliability and operational continuity of the compressor. Overall, the observed cost structure reflects the inherent limitations of traditional compressors, particularly their dependence on oil-based lubrication systems and the high frequency of maintenance operations.

IV.3.1.1.2. System Reliability Analysis

Compressor reliability is assessed using the mean time between failures (MTBF). According to available data, the compressor operates for approximately 8000 hours per year and experiences an average of three failures per year.

This results in an estimated MTBF of approximately 2667 hours, corresponding to the average operating time between two successive failures. This value allows us to assess the reliability level of the conventional compressor and highlights the influence of mechanical wear and the system's complexity on the frequency of failures.

$$\boldsymbol{MTBF = \frac{T}{N} = \frac{8000}{3} = 2667 \text{ hours} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (IV.8)}$$

IV.3.1.1.3. Study of the maintainability of the technical system

The compressor's maintainability is assessed using the Mean Time to Repair (MTTR), encompassing partial overhauls, complete overhauls, and corrective maintenance tasks. During a three-year operational cycle, the total downtime is projected to be 889 hours, averaging around 296 hours annually. This figure indicates the overall duration necessary to return the compressor to its standard operational state following failures or planned repair activities.

The findings demonstrate that substantial overhauls considerably impact total maintenance duration, underscoring the necessity of strategic maintenance planning to minimize system downtime and enhance operational efficiency.

$$\boldsymbol{MTTR = \frac{Tr}{N} = \frac{889}{3} = 296 \text{ hours} \ldots\ldots\ldots\ldots (IV.9)}$$

Table.IV.3. Maintenance Downtime Data of the Compressor

Maintenance Type	Duration (3 years)	Annual Equivalent (h/year)
Partial Overhaul (2×6 days)	**288 h**	**96 h/year**
Full Overhaul (20 days)	**480 h**	**160 h/year**
Corrective Maintenance	**120 h**	**40 h/year**
Total Downtime	**888 h**	**296 h/year**

IV.3.1.1.4. System Availability Analysis

The availability of the compressor is calculated from the ratio of Mean Time Between Failures (MTBF) to Mean Time To Repair (MTTR). The calculated parameters (MTBF = 2667 h and MTTR = 296 h) result in an availability of almost 90 %.

This result suggests that the compressor is working most of the time. However, the downtime due to maintenance operations and malfunctions is significantly affecting the total system performance. The comparatively high MTTR is the reason for lowering the availability level of the conventional compressor.

$$A = \frac{MTBF}{MTBF+MTTR} = \frac{2667}{2667+296} = 0.90 \approx 90\% \quad \text{(IV.10)}$$

IV.3.1.1.5. CAPEX (Capital Expenditure)

Capital expenditures (CAPEX) represent the initial cost allocated to the acquisition, installation, and commissioning of the centrifugal compressor system. These costs include the price of the main equipment, auxiliary systems, installation works, and commissioning operations required to achieve operation in accordance with industrial requirements.

For centrifugal compressors used in gas processing stations, CAPEX constitutes a significant portion of the total project investment. This is due to the complexity of such equipment and the integration of multiple auxiliary systems, such as lubrication, sealing, and control units. In this study, CAPEX is used as a key economic indicator to estimate the initial investment level of the conventional compressor system and to support a comprehensive techno-economic analysis [16-17].

Table.IV.4.Capital Expenditure (CAPEX) of the Compressor (BCL 406-A)

Component	Cost (DZD)
Compressor Package	**513 000000**
Installation	**108 000000**
Auxiliary Systems	**81 000000**
Commissioning	**40 500 000**
Total CAPEX	**742 500 000**

IV.3.1.1.6. Operational Expenditure (OPEX)

Operating expenditures (OPEX) related to the compressor primarily include energy consumption, maintenance activities, and production losses resulting from downtime periods. Energy consumption represents the direct operational cost associated with the compressor's operation under normal operating conditions. Maintenance costs, in turn, encompass expenditures related to spare parts, lubricating oils, as well as overhaul activities required to ensure the system's reliability and operational continuity.

Furthermore, production losses occurring during shutdown periods are considered an opportunity cost, representing the economic value of the ungenerated gas. These losses significantly contribute to the increase in the total cost of the compression system. The results show that indirect costs associated with system unavailability may exceed direct operating costs, highlighting the need to improve system availability and reduce the frequency of failures.

Table.IV.5. Operating Expenditure (OPEX) over a 3-Year Cycle

Cost Component	Value (DZD / 3 years)
Energy Cost	**1 036 800 000**
Production Loss (Gas Losses)	**1 166 400 000**
Maintenance Cost	**807 807 329**
Total OPEX	**3 011 007 329**

IV.3.1.1.7.Total Cost of Ownership (TCO)

The total cost of ownership (TCO) of a conventional centrifugal compressor over a three-year operating period includes both initial acquisition expenditures (CAPEX) and operating expenses (OPEX). The latter encompass energy consumption, maintenance costs, and production losses associated with downtime.

The results show that OPEX accounts for the largest share of the total cost, significantly exceeding the initial investment. Within these operating costs, production losses due to unavailability and energy consumption are the main cost drivers.

These findings highlight that the overall economic performance of the compressor is not solely related to the level of initial investment, but rather depends on another key factor, namely its operational efficiency combined with its availability.

$$TCO = CAPEX + OPEX = 742\ 500\ 000 + 3\ 011\ 007\ 329 = 3\ 753\ 507\ 329\ DZD \quad \text{(IV.11)}$$

IV.3.2. For a reciprocating system equipped with magnetic bearings and dry gas seals.

The centrifugal compressor installed in the Hassi R'mel gas processing unit is equipped with magnetic bearings and dry gas seals, representing state-of-the-art technology in the field of gas compression. This type of compressor is distinguished by the absence of mechanical contact between the rotating shaft and stationary components, with the rotor being suspended by an active magnetic bearing system, Unlike conventional compressors, this system does not require oil lubrication to ensure bearing operation or sealing functions. The elimination of the oil circuit leads to the removal of associated auxiliary equipment such as pumps, filters, and cooling systems, resulting in a cleaner and more compact architecture.

Magnetic bearings impose no restrictions on rotational speed or acceleration, enabling operation at very high speeds. Equipment operating at speeds exceeding 20,000 rpm has been successfully deployed in centrifugal compression applications, improving performance optimization and increasing operational flexibility.

The use of dry gas seals ensures effective sealing while minimizing gas losses and preventing contamination of the process fluid. In addition, the reduction of friction-related losses and mechanical wear enhances energy efficiency and overall system reliability.

This compressor has been designed for continuous operation in harsh industrial environments, ensuring high availability and reduced maintenance requirements compared to traditional oil-lubricated systems [2-16].

Table.IV.6.Technical Characteristics of the Magnetic Bearing Compressor (Hassi R'Mel) [2].

Parameter	Value / Description
Compressor Type	Centrifugal Compressor
Location	Hassi R'Mel
Bearing Type	Magnetic Bearings (AMB)
Sealing System	Dry Gas Seals
Lubrication System	No lubrication required
Mechanical Contact	No contact
Maximum Speed	15 000 – 25 000 rpm
Power Consumption	7 – 8 MW
Efficiency	80 – 88 %
Flow Rate	3 – 4 million Nm^3/day
Pressure Ratio	8 – 12
Auxiliary Systems	Reduced
Energy Losses	Lower than conventional
Operating Mode	Continuous operation
Operating Hours	8200 h/year
Number of Failures	01 failures/year
Operating Cycle	10 years (82 000 h)

IV.3.2.1. Techno-Economic Assessment

This section presents an in-depth technical and economic study of the centrifugal compressor system installed at the Hass R'Mel site, incorporating Active Magnetic Bearings (AMB) and Dry Gas Seals (DGS). The aim of this study is to evaluate and quantify the operational and financial advantages provided by these technologies, by comparing them with conventional oil-lubricated systems, within the specific context of the high-pressure conditions of the Algerian gas transmission network. By correlating technical performance data with long-term economic indicators, this analysis assesses the impact of eliminating oil-related failures on the system's entire lifecycle [2].

The evaluation covers a set of advanced performance parameters, including the reduction of mechanical losses due to friction, the elimination of oil leakage, as well as the improvement in reliability enabled by the diagnostic capabilities integrated into magnetic bearing controllers. From an economic perspective, this study examines the relationship between initial investment (CAPEX) and the significant reduction in operational costs (OPEX), emphasizing lower energy consumption, the elimination of costs associated with lubricant supply and management, as well as the notable decrease in production losses resulting from an extended mean time between failures (MTBF).

The objective is to illustrate to what extent the integration of AMB and DGS technologies modifies the economic profile of the compressor toward a more efficient and sustainable model. By combining the precision of contactless rotational operation with reduced maintenance requirements, this approach enables the identification of key factors for optimizing system availability. Consequently, the following section provides an in-depth analysis of the maintenance strategy, examining the specific failure modes of electronic control units and sealing cartridges, in order to assess their impact on the total cost of ownership (TCO).

IV.3.2.1.1. Analysis of Maintenance Performance

Compressors equipped with magnetic bearings exhibit significantly lower maintenance costs compared to conventional systems, primarily due to the absence of oil lubrication and sealing subsystems. The elimination of mechanical contact between rotating and stationary components removes wear phenomena, which represent the main source of failures and maintenance interventions in traditional compressor systems.

Furthermore, the reduction in the number of auxiliary components, such as pumps, filters, and valves, simplifies the overall system architecture and consequently reduces the probability of failure. This leads to a significant decrease in both scheduled and unscheduled maintenance activities, resulting in a corresponding reduction in annual operating costs.

This optimization of maintenance requirements improves the system's operational efficiency and enhances its economic performance over the entire lifecycle [2].

Table.IV.7.Annual Maintenance Cost of the Magnetic Bearing Compressor

Cost Component	Value (DZD/year)
Lubrication System	0
Spare Parts	10 200 000
Maintenance Labor	1 500 000
Preventive Maintenance	80 000 000
Corrective Maintenance	30 000 000
Unplanned Maintenance	12 735 000
Total Maintenance Cost	**134 435 000**

IV.3.2.1.2. System Reliability Analysis

The reliability of the magnetic bearing compressor is characterized by a low failure rate as well as stable operating conditions over time. According to the available operational data, the equipment operates approximately 8,200 hours per year, with an average of one failure per year, corresponding to a mean time between failures (MTBF) of about 8,200 hours.

Over a ten-year period, the total number of failures remains limited, which demonstrates the robustness and reliability of the system. This performance is mainly due to the absence of mechanical contact and lubrication systems, thereby eliminating wear phenomena and reducing the probability of failure [2-16].

The low frequency of failures contributes to a high system availability rate, ensuring continuous operation and reducing downtime. These characteristics make the magnetic bearing compressor a highly reliable solution for industrial applications requiring high operational stability.

$$MTBF = \frac{T}{N} = \frac{8200}{1} = 8200 \text{ hours} \quad \text{(IV.12)}$$

Table.IV.8.Reliability Indicators of the Magnetic Bearing Compressor

Indicator	Value
Operating Time	8200 h/year
Failure Rate	1 failure/year
MTBF	8200 h
Lifetime	10 years
Total Failures	10 failures
Availability	Very High

IV.3.2.1.3. Study of the maintainability of the technical system

The maintenance of the magnetic bearing compressor is significantly facilitated compared to traditional systems, due to its streamlined design and the limited number of mechanical components. The elimination of lubrication and oil sealing systems removes several subsystems that typically require regular maintenance operations.

Maintenance interventions are therefore limited and less complex, mainly consisting of periodic inspections and supervision of the control system. As a result, the mean time to repair (MTTR) remains relatively short, estimated at approximately 24 hours.

Furthermore, the reduced requirements for spare parts, together with improved accessibility to system components, enable faster and more efficient maintenance operations. These features enhance the overall maintainability of the compressor and support uninterrupted operation with minimal downtime.

$$MTTR = \frac{Tr}{N} = \frac{24}{1} = 24\ hours \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(IV.13)}$$

The MTTR (Mean Time To Repair) of the magnetic bearing compressor is calculated in the same way as that used for the conventional system. Assuming an average repair time of about 24 hours and one failure per year, this would give an MTTR of 24 hours.

Compared to the traditional compressor, whose MTTR is significantly higher, the magnetic bearing system leads to a substantial reduction in repair time. This improvement is mainly due to the simplicity of the design and the absence of subsystems associated with lubrication, allowing for faster and more efficient maintenance interventions.

IV.3.2.1.4. System Availability Analysis

The availability of the magnetic bearing compressor is assessed based on the relationship between the mean time between failures (MTBF) and the mean time to repair (MTTR). Using the adopted values (MTBF =8,200 hours and MTTR = 24 hours), the estimated availability is approximately 99.7%.

This result reflects a high level of operational efficiency, with the compressor remaining available for nearly its entire operating time. However, considering the typically expected performance of magnetic bearing systems, this value may be regarded as relatively moderate. Indeed, such systems are generally associated with higher reliability and significantly reduced maintenance requirements.

The relatively short MTBF and comparatively long MTTR suggest that external factors, such as system configuration, operating conditions, or maintenance policies, may substantially influence overall performance. Under optimal conditions, magnetic bearing systems are expected to exhibit significantly higher availability, primarily due to reduced mechanical wear and simplified maintenance operations [16]

$$A = \frac{MTBF}{MTBF+MTTR} = \frac{8200}{8200+24} = 0.997 \approx 99.7\% \quad \text{(IV.14)}$$

IV.3.2.1.5. CAPEX (Capital Expenditure)

The investment costs associated with the magnetic bearing compressor system are divided into three main components: the magnetic bearing system, the integration of dry gas seals, and the reduction of auxiliary systems.

The magnetic bearing system represents the primary investment, as it replaces conventional mechanical bearings with a contactless support technology. In addition, dry gas seals ensure effective sealing while eliminating the risks of oil leakage and contamination. Furthermore, the auxiliary systems are significantly reduced compared with those of conventional compressors, since the elimination of lubricating oil makes complex pumping, filtration, and cooling equipment unnecessary.

Although these various components result in a relatively high initial investment cost, they contribute to the development of a more compact, efficient, and reliable compression system [15-16].

Table.IV.9.Capital Expenditure of the Magnetic Bearing Compressor System

Component	Cost (DZD)
Compressors (BCL 406-A)	714 807 330
Magnetic Bearing System	120 000 000
Dry Gas Seals Integration	64 050 000
Auxiliary Systems (reduced)	5 400 000
Control	60 000 000
Total CAPEX	**964 257 330**

IV.3.2.1.6. Operational Expenditure (OPEX)

The operating costs of the magnetic bearing compressor are characterized by a significant reduction in expenses throughout the lifecycle, attributable to the elimination of lubrication systems and the reduction of mechanical losses. Maintenance interventions remain limited and are mainly confined to regular inspections, thereby contributing to the control of relatively moderate operating costs.

Furthermore, this system provides substantial economic benefits due to the optimization of energy efficiency and the reduction of losses, consequently generating net operating savings over a ten-year operating period. These results highlight the considerable economic importance of magnetic bearing technology in industrial compressor applications [2].

Table.IV.10. Operating Expenditure (OPEX) over a 10-Year Cycle

Indicator	Value (10 years)
Maintenance Cost	134435 000
Electrical Energy	1 650960 000
Total OPEX	**1 785 395 000 DZD**

IV.3.2.1.7. Total Cost of Ownership (TCO)

The Total Cost of Ownership (TCO) of the magnetic bearing compressor over a ten-year period includes both the initial investment and the operational expenditures associated with maintenance activities.

The TCO inevitably remains positive, as it represents the total expenses incurred throughout the entire lifecycle of the system. Nevertheless, it is important to emphasize that this type of compressor enables significant operating savings through reduced maintenance requirements and improved energy efficiency.

Although these savings are not directly incorporated into the evaluation of the Total Cost of Ownership (TCO), they contribute substantially to the optimization of the overall economic performance of the system [15-16].

TCO = CAPEX + OPEX =964 257 330+ 1785 395 000 =2 749 652 330 DZD…………(IV.15)

IV.4. A COMPARATIVE ANALYSIS OF THE TECHNICAL AND ECONOMIC CRITERIA FOR CENTRIFUGAL COMPRESSORS IN THE HYDROCARBON INDUSTRY

IV.4.1.General Context of the Comparative Analysis

This section presents a comparative techno-economic analysis between a conventional centrifugal compressor and a compressor equipped with magnetic bearings combined with dry gas seals. The evaluation is based on several key performance indicators, including investment and operating costs, maintenance requirements, as well as system reliability and availability.

The purpose of this study is to examine the influence of these advanced technologies on the overall efficiency and profitability of the compression system. In this context, the analysis relies on quantitative data and graphical representations intended to highlight the major differences between the two configurations

IV.4.2. Discussion of Results

The comparative techno-economic assessment notably highlights the superiority of the magnetic bearing centrifugal compressor over the conventional lubricated system. The results obtained indicate that the elimination of the oil circuit, a characteristic feature of magnetic technology, is a key factor in simplifying the overall system. This simplification directly leads to a reduction in maintenance operations, lower associated costs, and a significant decrease in unplanned interventions.

This technological advancement is also reflected in reliability indicators. Indeed, the increase in mean time between failures (MTBF), combined with the reduction in mean time to repair (MTTR), reflects an overall improvement in system operational reliability. These performance gains ensure a high availability level for the magnetic bearing compressor, approaching 99.7%, which represents a major advantage in continuous industrial processes, particularly in gas processing, where any downtime results in direct and substantial economic losses [16].

Furthermore, the incorporation of magnetic bearings, by eliminating mechanical friction as well as losses associated with lubrication systems, significantly enhances overall energy efficiency. This reduction in internal losses, combined with the removal of auxiliary subsystems such as oil circulation and conditioning, leads to optimized energy consumption and lower operating costs over the entire lifecycle [15]. Consequently, technological improvements are directly translated into sustainable economic benefits, strengthening the competitiveness of this technology.

However, although the conventional centrifugal compressor is based on a proven and widely adopted industrial technology, its performance remains limited due to intrinsic design constraints. The presence of mechanical contact surfaces, as well as reliance on lubrication systems, generates higher maintenance requirements, increased downtime, and additional energy losses. These constraints negatively affect its availability and lead to a higher total cost of ownership.

In summary, the combination of magnetic bearings with dry gas sealing systems results in a significant technological transformation of the centrifugal compressor, jointly optimizing its reliability, energy efficiency, and economic viability. The findings of this study confirm that the integration of this advanced technology represents an effective solution for improving technical performance while substantially reducing lifecycle costs in industrial centrifugal compressor applications.

IV.4.2.1. Maintenance Analysis

The study of maintenance strategies reveals a marked distinction between the traditional centrifugal compressor and the one equipped with magnetic bearings, both in terms of technical architecture and operational and economic performance. The traditional system relies on a sophisticated lubrication chain comprising oil pumps, filters, separators, and sealing devices. Although this architecture is technologically proven, it generates several potential sources of malfunction attributable to mechanical wear, contamination of the lubricating fluid, and the gradual deterioration of auxiliary components. Consequently, it leads to an increase in preventive and corrective maintenance operations, as well as higher direct and indirect costs related to production downtime.

In contrast, the magnetic bearing compressor is characterized by a contactless design, entirely eliminating the need for lubrication. This feature represents a major technological advancement, as it removes a substantial portion of the classic failure mechanisms (oil leaks, filter clogging, auxiliary pump failures, seal degradation). The simplification of the overall system results in a structural reduction in maintenance interventions, whether preventive or corrective, as well as a significant decrease in logistical complexity related to operation.

From an interpretative perspective, the obtained results reflect an overall improvement in the operational reliability of the magnetic system, characterized by increased service continuity and reduced periods of downtime. The reduction in maintenance operations directly impacts shutdown durations, thereby optimizing operational availability and strengthening the stability of the industrial process. Furthermore, the elimination of lubrication subsystems contributes not only to lower operating costs but also to a reduction in the risk of progressive failure, thereby increasing the predictability of system behavior throughout its lifecycle.

During the examined operating period, the magnetic bearing compressor thus demonstrates a notable advantage in terms of maintenance efficiency, reduced downtime, and lifecycle cost optimization. These results confirm that the transition toward contactless technologies represents a key factor in optimizing the overall performance of compression systems, particularly in industrial contexts requiring high availability and continuous operation.

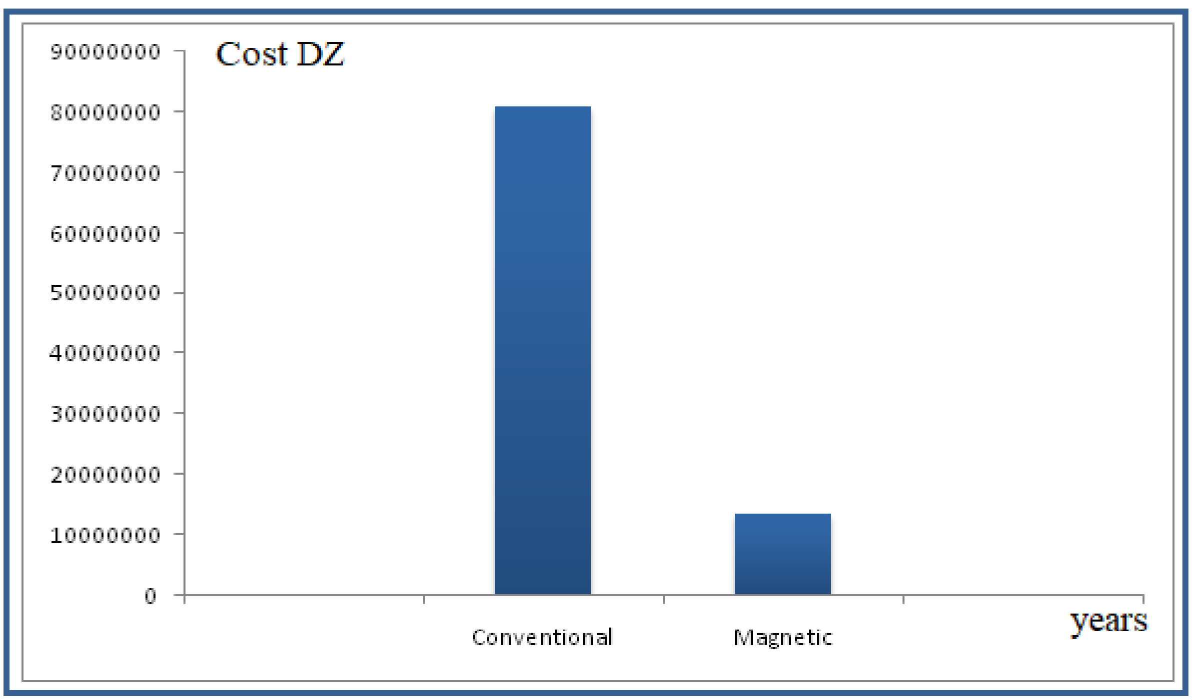

Fig.IV.2.Maintenance Cost Comparison between Conventional and Magnetic Bearing Compressors

The study of maintenance strategies reveals a notable divergence between the conventional centrifugal compressor and the compressor equipped with magnetic bearings. The conventional system relies on a set of lubrication mechanisms, including oil pumps, filters, and seals, which require periodic maintenance operations and are subject to mechanical wear phenomena. This configuration leads to increased maintenance costs as well as a higher frequency of interventions.

In contrast, the compressor with magnetic bearings operates on a non-contact levitation principle, making any lubrication system unnecessary. This feature eliminates many potential sources of malfunction and significantly reduces maintenance interventions, whether preventive or corrective. This results in a substantial reduction in maintenance-related costs, as well as improved operational stability of the system.

During the analyzed operating period, the magnetic-bearing system is characterized by increased maintenance efficiency, reduced downtime, and lower maintenance requirements over the entire life cycle.

IV.4.2.2. Reliability Analysis

The reliability assessment reveals a clear superiority of the compressor equipped with magnetic bearings. The mean time between failures (MTBF) is significantly longer for the magnetic system, reaching 8,200 hours, compared with the conventional compressor, which has a lower MTBF.

Furthermore, the mean time to repair (MTTR) is significantly reduced in the magnetic-bearing system, due to optimized maintenance procedures and the absence of components subject to mechanical wear. This optimization enhances the overall robustness of the system and reduces downtime periods.

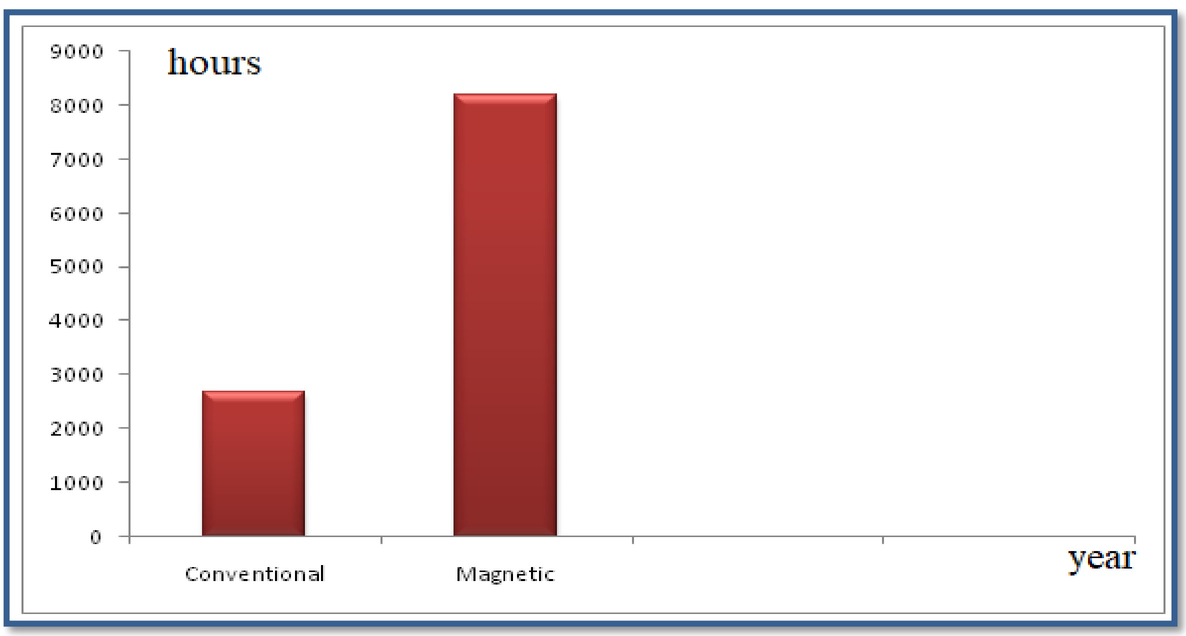

Fig.IV.3. Mean Time Between Failures (MTBF) Comparison

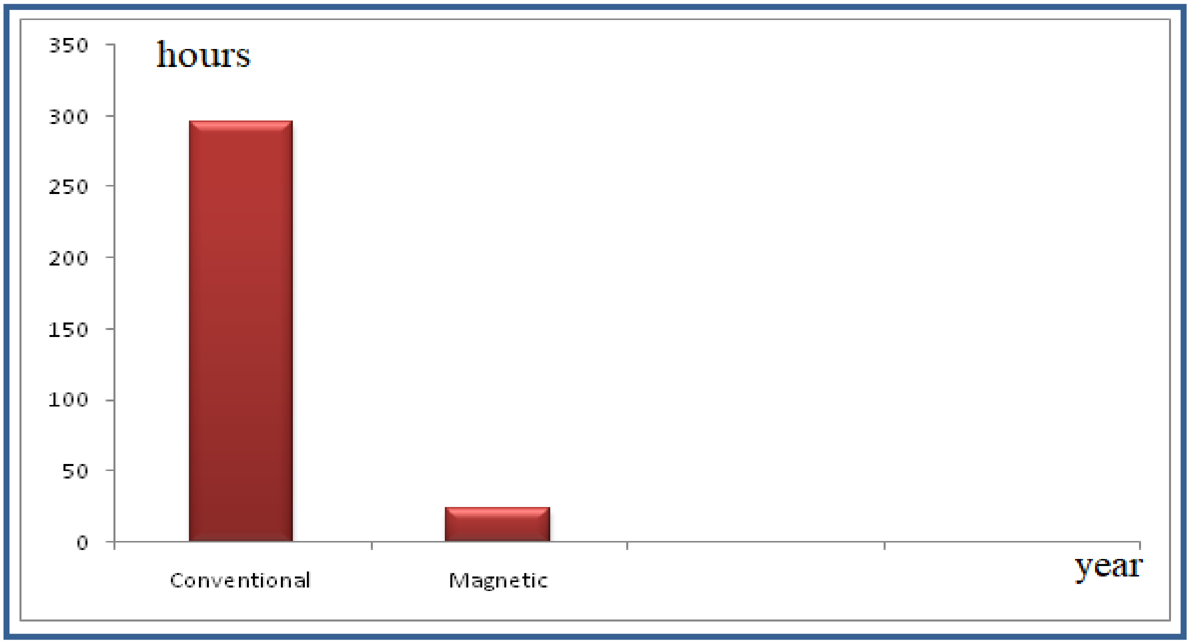

Fig.IV.4. Mean Time To Repair (MTTR) Comparison

IV.4.2.3.Availability Analysis

The results regarding availability highlight the operational advantage of the magnetic bearing compressor. With an availability rate of approximately 99.7%, this system operates continuously and in a stable manner.

In contrast, the conventional compressor shows lower availability due to a higher number of failures and longer intervention and repair times. This disparity directly affects production continuity and the overall performance of the system in industrial applications.

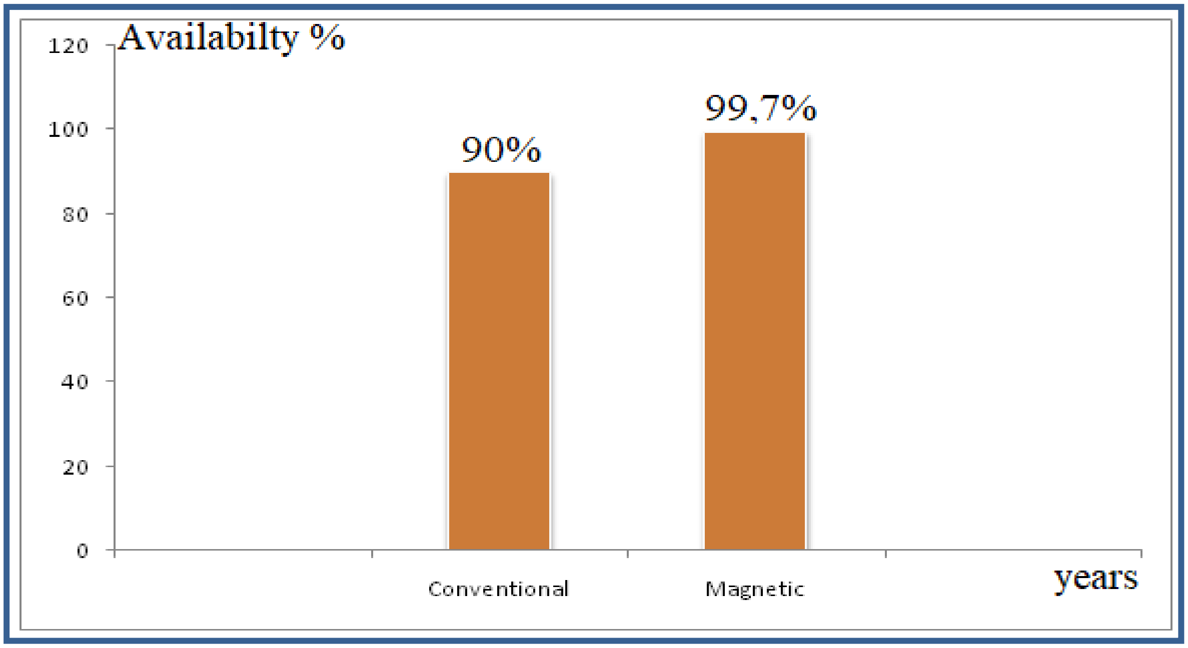

Fig.IV.5. System Availability Comparison

IV.4.2.4. CAPEX (Capital Expenditure)

The analysis of capital expenditures shows that the magnetic bearing compressor requires a slightly higher initial investment than the conventional system. This difference is mainly explained by the integration of advanced technologies, such as magnetic bearings and dry gas seals, which enhance system efficiency while also increasing overall complexity.

However, this increase in initial cost should be considered in light of the associated structural and functional benefits. Indeed, this technology eliminates the need for several auxiliary systems, particularly lubrication units, resulting in a more compact, simplified, and technologically advanced architecture.

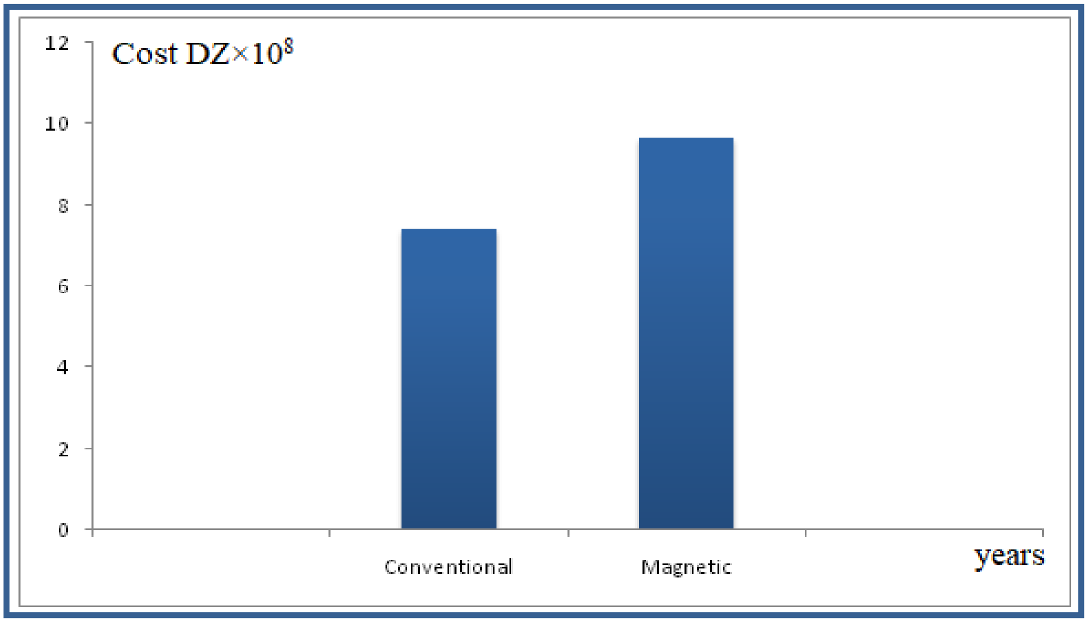

Fig.IV.6. Capital Expenditure (CAPEX) Comparison

IV.4.2.5. Operational Expenditure (OPEX)

The analysis of operating costs highlights a significant net economic benefit in favor of the magnetic bearing compressor. The conventional system indeed incurs high operating costs, mainly due to maintenance operations and associated energy losses. In contrast, magnetic bearing technology considerably reduces these expenses.

This economic advantage is largely attributable to the absence of a lubrication system and to the reduction of mechanical friction phenomena. These features result in very limited maintenance requirements, leading to lower operating costs over the entire service life of the compressor.

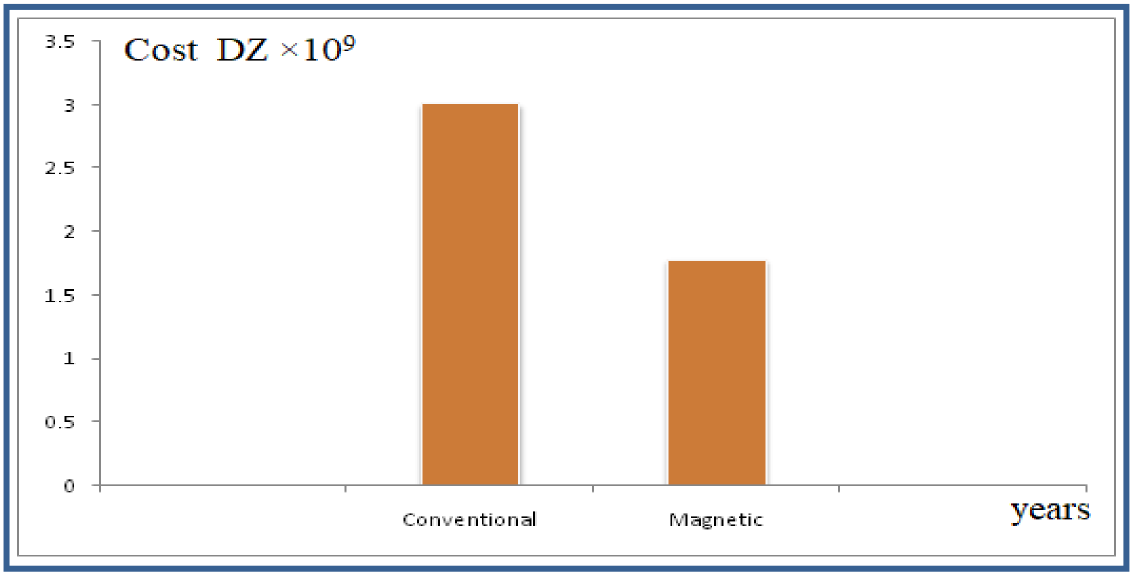

Fig.IV.7. Operating Expenditure (OPEX) Comparison over 10 Years

IV.4.2.6. Comparative Study of Total Cost of Ownership Differences Between Conventional Bearings and Magnetic Bearings

The study of Total Cost of Ownership (TCO) over a ten-year period shows that, although magnetic bearings require a higher initial investment, they result in a lower overall cost compared to conventional bearings. This difference is mainly due to the reduction in energy losses, the elimination of lubrication systems, and the decreased maintenance requirements.

Since operating expenditures (OPEX), particularly energy consumption, account for the majority of life-cycle costs, the TCO of conventional solutions increases more significantly. Consequently, magnetic bearings emerge as a more economically advantageous option in the long term..

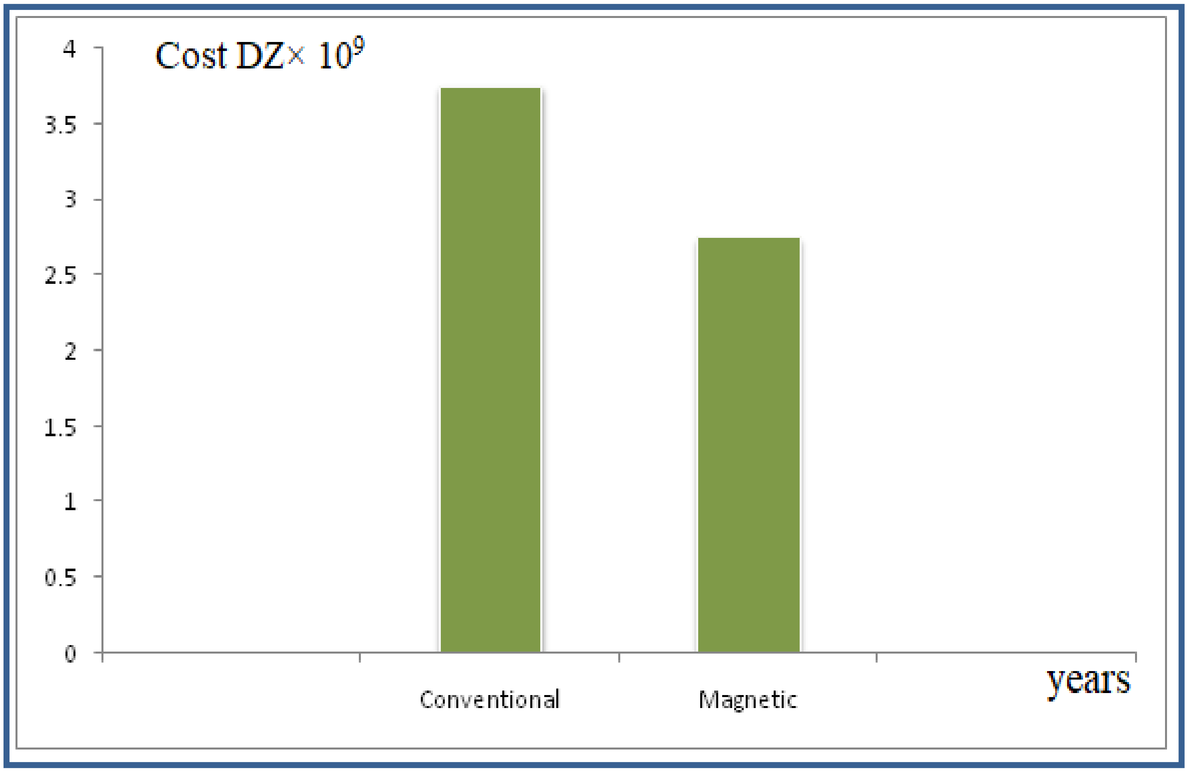

Fig.IV.8.TCO Comparison between Conventional Bearings and Magnetic Bearings over 10 Years

IV.5. CONCLUSION

In summary, the comparison between the conventional compressor and the magnetic bearing compressor reveals significant differences from a technical, operational, and financial perspective, highlighting the fundamental impact of magnetic bearing technology on the overall system efficiency.

In terms of reliability, the obtained results demonstrate a clear improvement in favor of the magnetic bearing compressor. It exhibits a substantially higher MTBF (8200 h compared to 2667 h for the conventional technology), indicating a significant reduction in failure frequency. At the same time, a marked decrease in MTTR is observed (24 h instead of 296 h), reflecting faster, less complex, and better-controlled maintenance operations. Together, these two indicators result in an almost optimal operational availability of approximately 99.7%, ensuring significantly improved service continuity and a substantial reduction in unplanned downtime.

From an economic standpoint, although the initial investment (CAPEX) of the magnetic bearing compressor is higher, life-cycle analysis clearly demonstrates the superiority of this solution. The reduction in operational (OPEX) and maintenance costs more than compensates for the higher upfront investment, resulting in a decrease in the total cost of ownership (TCO) of approximately 1,003,854,999 DZD over the studied period. This economic optimization is primarily driven by fewer corrective interventions, reduced production losses due to downtime, and improved operational efficiency.

Overall, the results show that despite the higher initial investment, the magnetic bearing compressor is a technologically advanced, more reliable, and economically advantageous solution in the long term. This technology therefore represents a strategically relevant option for industrial environments requiring high availability, reduced operating costs, and sustainable optimization of overall performance.

GENERAL CONCLUSION

GENERAL CONCLUSION

Centrifugal compressors are among the most important rotating machines used in the oil and gas industry due to their crucial role in gas transportation, processing, and storage systems. Their performance has a direct impact on production continuity, operational reliability, energy consumption, and maintenance costs. Therefore, improving the efficiency and reliability of centrifugal compressors has become one of the major industrial and technological challenges [3-4].

Conventional centrifugal compressors generally operate using oil-lubricated bearing systems. Although these systems are widely employed in industrial applications, they suffer from several limitations related to mechanical friction, wear, vibrations, lubrication requirements, and frequent maintenance operations. Furthermore, oil lubrication systems increase operational complexity and may create environmental and safety concerns because of leakage risks and the need for auxiliary equipment [3-6].

In recent years, magnetic bearing technology has emerged as an advanced solution for improving the performance of high-speed rotating machinery. Unlike conventional bearings, magnetic bearings operate without mechanical contact, which significantly reduces friction losses and mechanical wear. Their integration into centrifugal compressors contributes to enhanced dynamic stability, lower vibration levels, improved operational reliability, and reduced maintenance requirements.

Moreover, the techno-economic study conducted within the framework of this research highlights the significant economic advantages associated with the integration of magnetic bearings into centrifugal compressors. Although this technology requires a relatively high initial investment due to the cost of electronic control equipment, sensors, and associated control systems, the results demonstrate that these expenses are largely offset by the benefits achieved during the operational phase.

Indeed, magnetic bearings considerably reduce losses caused by mechanical friction, wear of rotating components, and the periodic maintenance interventions generally required in conventional oil-lubricated systems. This reduction in maintenance requirements directly contributes to improving compressor operational availability, minimizing unplanned shutdowns, and optimizing production continuity.

The results of the techno-economic evaluation showed that the maintenance cost reduction rate is 16.64%, corresponding to an overall saving estimated at approximately 673,372,329 DZD over the compressor life cycle. Moreover, the analysis of the results indicates that the life cycle cost savings rate is 26.74%, which demonstrates an increase in the overall profitability of the system. In addition, the corresponding financial benefit is estimated at 1,003,854,999 DZD, highlighting the positive long-term economic impact of the studied solution. This reduction in operating costs is mainly attributed to the elimination of auxiliary lubrication systems, the decreased replacement frequency of wear-prone components, and the lower costs associated with corrective and preventive maintenance operations.

Therefore, the obtained results confirm that magnetic bearings represent an efficient, reliable, and economically advantageous technological solution for the modernization of centrifugal compressors used in the oil and gas industry. Their implementation not only improves the dynamic and energy performance of rotating machinery but also reduces the total cost of ownership while increasing the reliability and durability of industrial installations.

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