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Retrofit of a Heat Pump Unit†

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Abstract: With a constant increase in Heat Pumps (HP) use it has become of great importance the application of Fault Diagnosis (FD) methods to detect faults at an early stage, and thus ensure a proper working condition and improve reliability of the equipment. The present paper addresses a FD and retrofit of a water-to-water HP unit. The faulty equipment, completely out of operation, was entirely analyzed and a catastrophic failure in the three-phase compressor was identified. After identifying the faulty component, it was concluded that it should be replaced. Thereby, an adequate solution for this HP is retrofitting with a smaller capacity compressor, which is more suitable for the considered environment. The replacement is also motivated by the fact that the equipment cannot even be started without tripping the circuit breaker. To detect and identify the faults, the electrical part was analyzed first, starting with the verification of the components in the electrical circuits. After that, the resistance of each one of the windings was measured and it was concluded that they were out of the manufacturer's specification. The process of retrofitting with a new unit followed some steps. First, it was considered the thermal loads required for the environment and then, a suitable compressor capable to fulfill such requirements was selected. This selection considered the compatibility with the other system's components. Finally, to avoid future faults and failures, after retrofitting with the new compressor, temperature sensors will be installed to be used as a basis for virtual sensors which enable an efficient FD approach.

Keywords: Heat Pump (HP); Fault Diagnosis (FD); Compressor; 3-phase motor

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1. Introduction

A Heat Pump is a device that uses a vapor-compression cycle to transfer heat from a cold source to a hot one (as long as they are independent). The first studies on HP were conducted by Carnot and Kelvin in the mid 1800's. However, only in the third decade of 1900's more practical and viable models for the public were developed [1, 2]. Statistics show that between 2005 and 2014 more than 7 million HP units were sold in the EU [3]. The growing tendency of sales is mostly explained by their high efficiency and capability to comply with the new legislations. As an example of their efficiency, for domestic hot water, HP can reduce primary energy consumption (natural gas, uranium, coal), when compared to a boiler, by 15–20% [2].

Fault diagnosis on HP is important as is being progressively more used not only at residential level but also in commercial buildings. In present-day, the words "savings", "low budget" (and other …) are mandatory on a daily basis. So, repairing an equipment part is, sometimes, a more economical option instead of an entire unit replacement. Although repairing a HP can be viable, the best option is to prevent faults that may lead to failures by adopting adequate maintenance strategies. This way, the lifespan of a HP may be increased while the repairing costs can be reduced. It can be accomplished by not getting costly and catastrophic failures (like a seizing compressor unit). Moreover, indirect costs can be avoided by the adoption of a proper maintenance (for example, places that require a constant temperature due to their sensitivity to variations). Some of the main faults of a HP are mechanical and regard: a) condenser and/or evaporator fouling; b) refrigerant leakage; c) improper charge; d) compressor valve leakage, e) liquid line restriction, e) non-condensable gases, and, in reversible systems, f) 4-way valve leakage and g) check valve leakage. [4,7].

Additionally, there are also control and electronics faults in HP systems, which are the most common and costliest faults. These faults are related to the control unit, electrical faults, printed circuit board, overcurrent, and motor protection relay, etc. [8]. The present work describes the fault diagnosis of a HP unit, including all the intrinsic aspects, such as detection, localization, identification, and severity assessment [9], and its retrofit based on a corrective maintenance strategy.

2. Materials and Methods

In this chapter, it will be studied the main components of a HP in order to understand how it works and how some of the faults may occur. Then, it will be presented the analyzed case-study.

2.1. Heat Pumps

2.1.1. Operation of a HP

Heat pumps move heat from one heat source to another. For example, a heat pump is used for adding heat to a building during the cold season and removing it during the cooling season. In order to have this energy transfer, it is necessary to introduce work in the system.

There are two major groups of HP: reversible and irreversible HPs. Reversible HPs are the ones that have the capability to cool or heat a place. In other words, during the summer they act as an air conditioner and in the winter, as a HP. Meanwhile, the irreversible HP doesn't have the capability of cooling, only heating (such as a HP used for domestic hot water, for example).

HPs used the refrigeration cycle to transfer heat. This cycle is characterized in the T-s and P-h diagrams by having four stages:

1. Compression;
2. Condensation;
3. Expansion;
4. Evaporation.

Figure 1 represents the ideal refrigeration cycle.

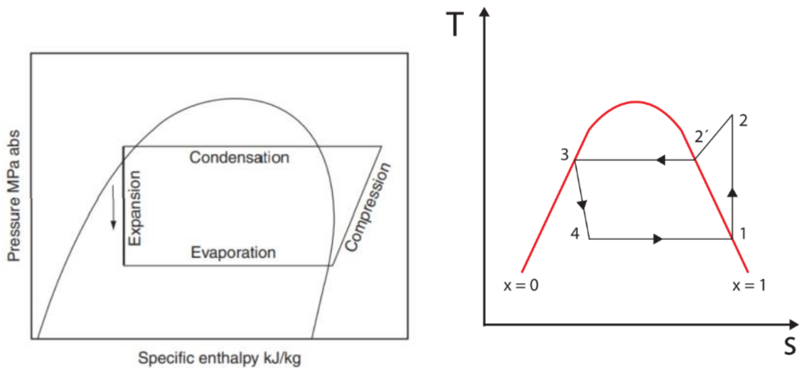

Figure 1. P-h diagram (**a**) and T-s diagram (**b**) for an ideal refrigeration cycle [1 0,11].

From 1 to 2 occurs isentropic compression, where it is introduced work to the fluid by the compressor. Then, from 2 to 3, there is an isobaric condensation at the condenser, where heat is removed from the refrigerant. At the expansion valve (stage 3-4) the fluid expands due to a pressure drop, what results, consequently, in a temperature drop. In the last stage, 4 to 3, the refrigerant vaporizes by absorbing heat in the evaporator and the cycle restarts and repeats constantly while the HP is working [10].

This cycle is valid for an irreversible HP. For a reversible HP, the cycle is mostly the same. However, it has a valve that inverts the refrigerant flow direction and switches the condenser and evaporator functions. Figure 2 represents a reversible HP (a) and an irreversible HP (b)

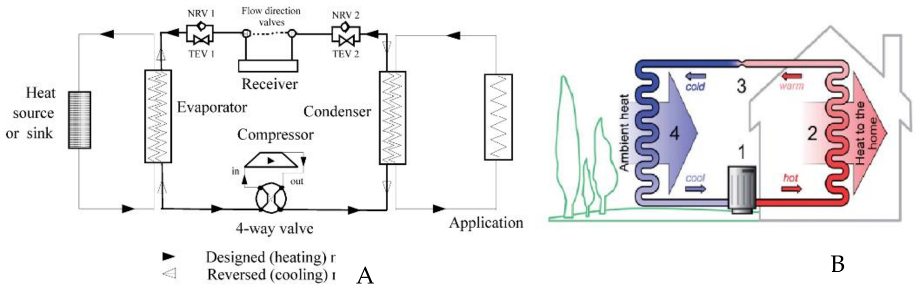

Figure 2. Reversible HP (**a**) and irreversible HP (**b**) schematics [2, 12].

Heat pumps can also be classified according to their heat source. They are divided into two major groups: Air Source HP and Ground Source HP. The first ones use the outside air as heat source and the latter ones use the ground (soil or water) as heat source.

2.1.2. Components of a HP Unit

HPs have four main components:

5. Compressor;
6. Condenser;
7. Expansion Valve;
8. Evaporator;

There are many types of compressors used in HPs. To choose the right one for a HP it is necessary to have some requirements as thermal load, refrigerant use, application and so on. Reciprocating compressor is a compressor that uses a piston to compress, driven by a crankshaft. Rotary compressors, instead of an up and down motion to compress the fluid, use a rotating piston, eccentric to the cylinder. Screw compressors use two helicoidal rotors parallelly arranged to compress the fluid. Finally, scroll compressors use two scrolls to compress the working fluid where the fluid goes from the outside to the inside of the scroll to be compressed, exiting in the center of the scroll. Figure 3 represents the compressor types [13].

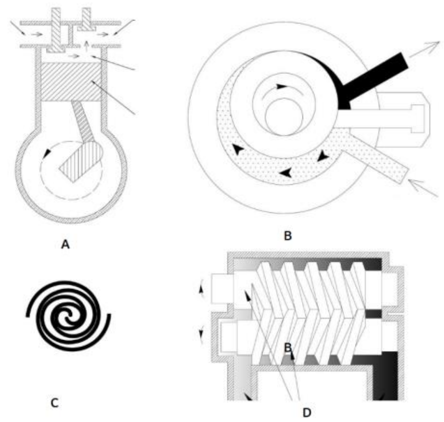

Figure 3. Compressor types: (a) reciprocating; (b) rotary; (c) scroll; (d) screw compressor [13].

The condenser and evaporator are simply heat exchangers which transfer heat from and to the fluid. For the condenser unit, they can be air cooled, and, in larger systems, water cooled. The main water-cooled heat exchangers are shell-and-coil, shell-and-tube, and double pipe. For the air-cooled units, the most used heat exchangers are plain or finned tubes. The evaporator units have two general types: dry and flooded. In the dry type, the refrigerant enters as a liquid and inside the evaporator, the fluid completely evaporates. For the flooded unit, a liquid-vapor mixture of the refrigerant fluid exists inside the evaporator.

Finally, the expansion valve is one major component for the HP. This device rates the flow of refrigerant from the high-pressure side to the low-pressure side. There are some types of expansion valves, like electronic controlled and thermostatic controlled expansion valves. They operate to maintain an adequate refrigerant flow at the evaporator [14].

2.1.3. Faults Presents in HP Units

The main faults that may occur in a HP unit are condenser and evaporator fouling, compressor valve leakage, refrigerant leakage, improper refrigerant charge, liquid line restriction, non-condensable gas, and, for reversing systems, reversing and check valve leakage. Moreover, there are also several electrical faults in HP systems that often occur due to mechanical faults. For example, the most common electrical fault in a HP is the failure of the compressor electrical motor. Such fault may result of liquid slugging in the compressor or the deterioration of the motor windings and its insulation due to high operations temperatures, both mechanical faults [15].

All the faults mentioned above are not immediate and, most of the time, not noticeable until the unit stops working or the desired performance is not achieved. These faults can be prevented through a proper maintenance schedule. All these faults are noticed by a reduction of the Coefficient of Performance (COP) and system capacity, which. will drop significantly [4].

2.1.4. Testing Environment

The HP unit under consideration is located at the Guarda International Research Station on Renewable Energies (GIRS-RES) facilities of CISE – Electromechatronic Systems Research Centre. The HP is from AVENIR ENERGIE and is a reversible water-to-water HP with the reference 34T GI IC. The main characteristics of this HP are: heating capacity of 38.46 kW, and cooling capacity of 27.93 kW. It operates with approximately 5 kg of R407C refrigerant fluid which is an HFC. It works with a scroll compressor with an electric power of 10 kW. Figure 4 represents the HP unit. The analyzed equipment presented at least an electrical fault to be diagnosed since it was not able to start.

Figure 4. Avenir Energie HP [16].

3. Methods

The methodology applied to this case was the process of a FD. In the first place, the fault was detected as every time the HP tried to start it would trip the breaker. Then, to detect where the fault was, the entire system was checked starting with the electrical system. The electrical system from this HP has two parts: The power circuit and control circuit. At an initial stage, all the components from the control side were tested: Two contactors, a timer, two flow switches and the junction box. Then, continuity was measured in every cable to ensure that there were no short-circuits. As the test values were within the specifications, the power circuit was then assessed, and all its continuities were checked.

The last component being tested was the compressor. According to the service manual, the internal resistance for each phase cannot be more than 0.3 Ω. The resistance obtained (taking into consideration the resistance of the multimeter) was 0.7 Ω for each phase. At this stage, the fault is detected at the compressor unit. It was tried to start it from a "soft starter" to ensure it was internally damaged. A spike in current upon start that kept tripping the brakers was obtained. Thus, it was confirmed that the compressor presented a catastrophic failure and required being replaced with a new unit as it is not serviceable.

4. Retrofit

To retrofit, the first step was to select a new compressor. As this HP was over dimensioned for its application, a less powerful compressor should be chosen to replace the faulty one. Based on that, considering the required thermal load in the facility, the legislations that resulted from the Paris Agreement in 2015, and the operation parameters, a 18 kW (60000 BTU) scroll compressor was selected as the best choice, half the power of the faulty unit. Such compressor also accepts the R-134a as the refrigerant, which presents, when compared to R-407C, a lower Global Warming Potential (GWP) and lower operation pressures. Furthermore, the R-134a is not a mixture whereas R-407C is. Being a zeotropic mixture, the properties of R-407C in case of leakage may be modified, what implies in the refrigerant total substitution.

Since the HP presents a thermostatic expansion valve as an expansion device, it also must be replaced. That is because its operation is directly dependent on the refrigerant parameters. Therefore, if the refrigerant is changed, the thermostatic valve must be changed as well.

The next step to retrofit the equipment is to recover the R-407C of the system. Once recovered, the refrigerant charge must be determined and verified if it is approximately at its rated charge. If the charge is the same, it could be reused, if it is higher, that is probably the cause of the compressor failure. If it is lower, there is a refrigerant leakage in the circuit that must be repaired, and the refrigerant is no longer adequate. Regardless, considering the GWP and operation pressures of R-134a, it is more suitable for this application.

Then, the current compressor and the thermostatic expansion valve must be replaced in the circuit by the new ones. Since the new compressor presents different inlet and outlet diameters, the piping must be adapted to fit it. Before introducing the refrigerant, it is extremely important to verify the system hermeticity to ensure there are no points of leakage.

The adequate charge of refrigerant in the system shall be determined experimentally. It regards the charge that enables the maximum COP. Attention to not overcharge the system is required, however, when overcharged, the COP of a system stagnates. Other systems parameters should also be constantly monitored. Based on that and following to the retrofit itself, an On-Condition Based Maintenance strategy, through virtual sensors based in low-cost sensors, shall be the next step of this work.

5. Results and Discussions

Considering the fact that HPs are becoming progressively more popular, the fault diagnosis and retrofit of such equipment should not be disregarded. On the contrary, fault diagnosis is crucial and may result in several savings and in the insurance of the equipment availability. Meanwhile, the HP retrofit presents a profitable opportunity to improve an equipment or even to establish a corrective maintenance making it operational again.

Based on that, a faulty water-to-water HP was analyzed. Through a verification of the control and power circuits, a catastrophic failure in the compressor was diagnosed and it was determined that the compressor should be replaced. The retrofit of the equipment considered the operational, economic, and environmental aspects. Therefore, this retrofit presents not only the opportunity to achieve economic benefits, but also environmental ones since a lower charge of a lower GWP refrigerant is considered.

Finally, for future work, the retrofit must be totally completed and experimentally assessed. Additionally, in order to monitor the system and not only prevent, but also predict the early stages of such faults, virtual sensors based on low-cost sensors shall be installed.

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