Study of a Hybrid Wind-Diesel System with Compressed Air Energy Storage

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Abstract- **The electricity supply in remote areas around the world uses mostly diesel generators. This method, relatively inefficient and expensive, is responsible for the emission of 1.2 million tons of greenhouse gas (GHG) annually, only in Canada. Some low and high penetration wind–diesel hybrid systems (WDS) have been experimented in order to reduce the diesel consumption. The use of a high penetration system together with compressed air energy storage (CAES) it is a viable alternative to improve the overall percentage of renewable energy and reduce the cost of electricity. In this paper we compare different technical solutions for the CAES system and choose the one that optimize the performance and the cost of the overall system. While in this extended abstract only a superficial description of this system is introduced, detailed results of the simulation will be presented in the complete paper. This new design conducts to the increase of diesel power and efficiency, to the reduction of fuel consumption and GHG emissions, in addition to economies on the maintenance and replacement cost of the diesels.**

I. INTRODUCTION

In Canada, more than 200,000 people live in more than 300 remote communities (Yukon, TNO, Nunavut, islands …). It is necessary to add to that the many technical installations (towers and communications relays, weather systems), tourist facilities, farms which are not connected to the provincial or national electric distribution grids. This is the result of economic decisions related to the cost of transmission and distribution lines over a vast territory [1]. These isolated sites use diesels to generate electricity. This method is more expensive in itself than large electric production plants (gas, hydro, nuclear, wind …) and, on top of that, should be added significantly higher fuel transport costs. So, the diesel electricity production is relatively inefficient, expensive and responsible for the emission of 1.2 million tons of GHG annually in Canada only.

Indeed, the exploitation of these remote isolated grids shows a deficit in the order of hundreds of million of dollars per year that the government should support in a way or another. In Quebec alone, where the electricity tariff is uniform independent of the production price, Hydro-Quebec estimates at approximately 133 million dollars the annual losses for the supply of 14,000 subscribers divided in forty communities not connected to the main grid.

These deficits reflect the gap between the high costs of electricity produced from the diesel in these regions and the uniform price of the electricity. Furthermore, we estimate at 140,000 tons the GHG emission resulting from the use of generators for the subscribers of the Quebec autonomous networks. This quantity of GHG is equivalent to the one emitted by 35,000 cars during one year.

The majority of these communities are located in coastal areas and benefit of a good wind resource. The exploitation of the wind resource in these autonomous networks could reduce the deficits of exploitation by privileging the wind, a "local fuel", rather than the diesel, an imported fuel.

II. PRIMARY SOLUTION: HIGH PENETRATION WIND-DIESEL HYBRID SYSTEM (WDHP)

The use of hybrid systems, which combine renewable sources with the diesel generator, allows reducing the total consumption of fuel, an environmental and economic advantage.

Low penetration wind – diesel systems (WDS), have been already implemented in Nordic communities in Yukon [2], Nunavut [3] and in Alaska [4]. By low penetration systems we understand that the instantaneous wind power is maximum of 20-35% of the diesel rated power and the overall energy from wind do not exceed 10-15% of total consumption. Generally, the WDS uses an existing diesel power plant and add a wind farm containing a single model of turbine. To these two principal elements are added logic and the components necessary to the hybrid exploitation of the system: secondary loads for smoothing, regulator and automated command.

The increase of the wind penetration level allows better fuel reduction. However, the first obstacle with this perspective results from the operation constraints of diesels. Beyond a certain penetration level, it is necessary to maintain the diesel on stand by at over 30% of its nominal power output in order to respond to a sudden reduction of the wind. This limits the wind energy to a level of too weak penetration and the wind turbines act only as a negative charge for the network.

The high-penetration wind diesel systems without storage (WDHPWS) are those where the wind power production exceeds the charge for large periods of time [5]. This allows the complete stop of the diesels during those periods and conduct to a significant reduction of fuel consumption. In the mean time, this design is subject to complex technical problems [6], [7] which did that a single project of this type, without any storage, is presently operational in Alaska [4].

During some periods when the excess of wind energy over the charge is reduced, the diesel engine still must be maintained on stand by so that it could quickly respond to a wind speed reduction (reduce the time of starting up and heating of the engine). This is an important source of over consumption because the engine could turn during hours without supplying any useful energy.

For some situations [8], [9] the use of storage systems allows the overall cost of energy supply and increase the wind energy penetration rate (the part of wind energy in the total consumption during one year).

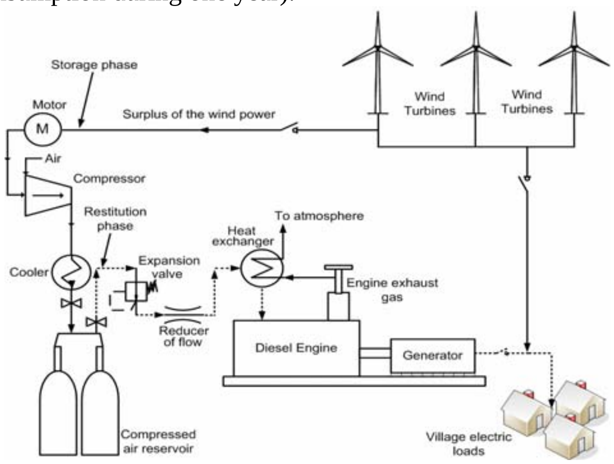

Fig. 1. Illustration of the WDCAS system

Presently, the wind energy excess is stored either as thermal (hot water), an inefficient way to store electricity as it cannot be transformed back in electricity when needed or in batteries which are expensive, difficult to recycle, a source of pollution (lead-acid) and limited in power and lifecycle. The fuel cells represent a viable alternative but the technical complexity, the prohibitive price and the weak efficiency delay acceptance by the market. The needed storage should be easily adaptable to the hybrid system, available in real time and smooth power fluctuations.

For this reason we examine the use of compressed air energy storage (CAES) with the wind-diesel hybrid system (WDCAS) (Fig. 1). The energy storage in the form of compressed air (CAES) is adaptable for the two sources of electricity production (wind energy and diesel). Moreover, the CAES presents an interesting solution for the problem of strong stochastic fluctuations of the wind power because it allows a high efficiency conversion (60-70% for a complete charge-discharge cycle), uses conventional materials easy to recycle and is able to make an almost unlimited number of cycles [10].

III. SUGGESTED SOLUTION FOR THE WDCAS

The proposed system, (WDCAS) combined with the diesel engine supercharge, will increase of the rate of penetration of the wind energy (RPWE). The supercharging is a process which consists, by a preliminary compression, in raising the intake air density of engines to increase their specific power (power by swept volume) [11]. During periods of strong wind, the surplus of the wind power (when wind power penetration rate defined as quotient between the wind generated power and the charge is greater than 1 – WPPR>1) is used to compress the air via a compressor and store it. The compressed air serves then to turbo charge the diesel engine allowing to increase its power and to decrease the fuel consumption. The diesel generator works during the periods of low wind, when the wind power is not sufficient for the load.

IV. VARIOUS METHODS OF SUPERCHARGING THE DIESEL USING THE STORED COMPRESSED AIR

Initially, it is necessary to mention that all the diesel engines used in remote areas (in Quebec) are already equipped with a supercharging system by turbo-compressor. On the other hand, this system loses its advantages during the operation at low regime because its effectiveness is directly related to the quantity of exhaust gases.

Several methods can be used to supercharge the diesel engines using the stored compressed air (CAS):

A. *System 1: Use of a turbine directly connected on the turbocharger shaft*

The compressed air, coming from the storage tank at few tens of bars, passes through a pressure reducer that reduces its pressure and its temperature (at few tens of degrees under 0°C). The air is then heated, initially by the system of cooling and then by exhaust gas from the outlet of the main turbine to increase its enthalpy. At the exit of heat exchangers, the air expands in the supplementary turbine coupled on the same shaft of the turbo-compressor (Fig. 2). This increases the couple available on the axis and so allows the compressor to supply a stronger compression ratio. The recovery of the exhaust gas allows increasing the efficiency of the system. The use of the compressed air going out of the reservoir to cool the water of the engine could further improve the overall efficiency by stopping the cooling ventilators.

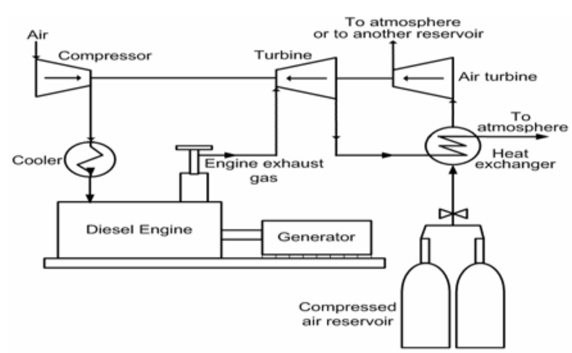

Fig. 2. Illustration of the WDSAC with the CAS turbine directly connected on the turbocharger shaft

B. *System 2:Two stage turbocharge*

A second stage (LP: low pressure) turbocharger is assembled and the compressed air expands in the LP turbine after having undergone the expansion and reheating by the cooling liquid of the engine and exhaust gas (Fig. 3). The HP (high pressure) and LP turbochargers do not have the same operating ranges, particularly the rpm. This method is characterized by the simplicity of sizing the turbines and compressors and the possible decoupling of the LP turbo-compressor when the CAES is not available. Consequently, the total efficiency of the system depends strongly on each of the efficiencies of the LP turbine and compressor.

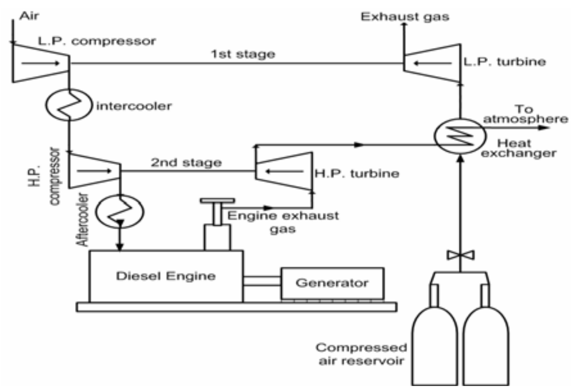

Fig. 3. Illustration of the two stage turbo charge

C. System 3: Admission of compressed air directly in the compressor

The compressed air expanded and heated by the cooling system of the engine and the exhaust gas, entry directly in the compressor of the turbocharger (Fig. 4). The main advantage is the use of a single turbo-compressor, so a better efficiency than the previous compression systems. Moreover, this method is characterized by its simplicity of design and control and by its reduced cost. However, the efficiency of this design depends strongly on the temperature of compressed air at the entry of the compressor (heated air = decline of the efficiency)

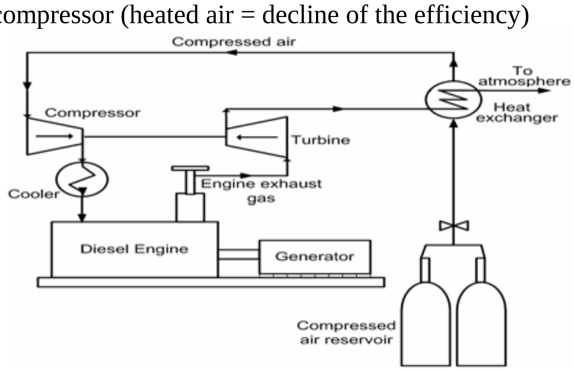

Fig. 4. Illustration of the admission of compressed air directly in the compressor

D. Systeme 4: Admission directly in the engine

This method consists in injecting the compressed air coming from the storage tank, after having it heated by the exhaust gas and the cooling liquid, directly in the cylinders through a third valve or in the intake collector where the air will be mixed with the one coming from turbo-compressor. A major inconvenient of this method is that requires a modification of the intake system to account for the new thermodynamic parameters of the air entering the cylinders.

E. System 5: Hyperbar turbocharger

The hyperbar process consists in supercharging the engine by a gas turbine (compressor + combustion chamber + turbine) arranged in derivation to the engine [12]. The air flow from the turbocharger system is controlled by a by-pass valve. An auxiliary combustion chamber allows increasing turbine power and, consequently, a higher ratio of supercharging pressure (Fig. 5). The by-pass valve is regulated so as to maintain constant the pressure difference between the exit of the compressor and the entry of the turbine. The flow rate of injected fuel into the combustion chamber allows controlling the pressure at the outlet side of the compressor [12]. This system, with its supplementary combustion chamber, is more complex to implement on existing diesel engines. Moreover, the efficiency of the system will tend to drop because of the additional contribution from the external combustion chamber. However, a remarkable increase in the power can be obtained [12].

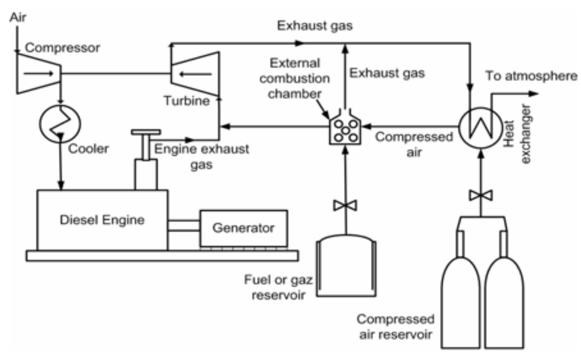

Fig. 5. Illustration of hyperbar turbocharger

F. System 6: Turbocharger based on pressurized LENOIR cycle

The proposed cycle uses the phases' succession of the Lenoir cycle: admittance, combustion, expansion and exhaust realized during a turn of engine's crankshaft and an isobar extracted from the Diesel cycle for the combustion [13]. The admittance of the high pressure air, from the storage tank, begins when the piston is at high dead point and finishes when the contribution of heat due to combustion starts. During the combustion, the volume increase of the cylinder and temperature increase of the gases, evolves in the same sense, the gas undergoes a transformation which in the theoretical cycle of this engine can be considered as isobar (1-2-3) or isochoric-isobar ($1'$-$2'$-$2''$-$3'$) (fig. 6) [14].

The advantage of this method is that the power of an engine functioning following a pressurized Lenoir-Diesel cycle is coarsely equal to four times the power of a conventional four-stroke engine [13]. However, this technique requires a time regulation of the admittance and exhaust valves and a modification of the admittance system, required by the injection of the compressed air coming from the reservoir at the adequate moment.

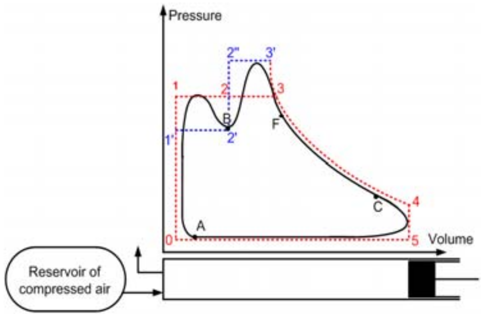

Fig. 6. Illustration of the LENOIR pressurized cycle

G. *Systeme 7:Turbocharging with downsizing*

The downsizing consists in reducing the swept volume with an aim of decrease the fuel consumption. In order to preserve the performances of the engine (couple, power) and to reward the loss for swept volume, it is necessary to increase the air filling of the engine. This is done using the supercharging by turbo-compressor. This supercharging-downsizing combination allows larger couple at low regime and increases the engine efficiency. However, this method could be applied only if actual engines are replaced, because of significant intervention to be made to the engines.

V. COMPARISON OF THE WDCAS SOLUTIONS

To evaluate the various solutions and choose the most interesting, we drew up a list of criteria such as:

1) Efficiency: the selected system must have a good efficiency;

2) Simplicity: the system must be simple and easy to install;

3) Adaptability: the selected system must be able to adapt to the actually installed engines without need to change their architecture;

4) Cost: the costs of installation of the selected system must be as low as possible;

5) Control system: the selected system must allow an easy control.

These criteria have been applied to the suggested technologies and are presented in Table 1. The criteria are equally important and a quote from 1 (worse) to 3 (best) has been allowed to each technology. According to table 1, the solution 1 is the best. The other systems are more or less effective, but it is on the level of the cost, the adaptability to the existing engines and ease of control that differences occur. For these reasons, we adopt this system to develop the WDCAS system.

TABLE 1
SELECTION CRITERIA OF THE COMPRESSED AIR TUBORCHARGING SYSTEM

Selection criteria	Importance	System 1	System 2	System 3	System 4	System 5	System 6	System 7
Efficiency	3	3	3	3	3	2	3	3
Simplicity	3	3	2	3	2	2	2	3
Adaptability with the diesel engine	3	3	2	2	2	3	2	1
Cost	3	3	2	3	1	1	1	3
Control system	3	3	2	3	2	2	2	3
Total	15	**15**	11	14	10	10	10	13

VI. TECHNICAL ADVANTAGES OF SOLUTION 1: USE OF A TURBINE DIRECTLY CONNECTED ON THE TURBOCHARGER SHAFT

The advantages of the proposed system are the simplicity and effectiveness. Also, the system does not require the engine modification. Moreover, it is not necessary to adapt the intake and the injection system with the new thermodynamic parameters of compressed air flow entering the cylinders. This design allows the cycle of supercharging to work independently of the engine while using the energy provided by the compressed air expanded in the air turbine. This system can increase the engine power by a factor of 5 and consequently the indicated efficiency of the engine. It is similar with a hyperbar system for the output power increase without needing an additional combustion chamber and fuel consumption [15]. Moreover, this system adapts to load variations while optimally benefiting of the hybridization between the turbocharger and the air turbine.

The hybrid supercharging, based on this design, can work under the following conditions:

1) Low regime – strong loads, for which the supplied energy from the exhaust gas would be insufficient to reach the required supercharging pressure;

2) Low regime – weak loads, during which the system will create the optimal thermodynamic conditions (temperature and pressure) necessary to the initiation of combustion, which the weak volumetric ratio of engine compression is not able to ensure.

3) Pneumatic starting, where the compressed air, coming from the storage tank, could be injected directly into the cylinders, using a by-pass valve, without passing through the air turbine, at a pressure ranging between 20 and 30 bar. This compressed air starts the engine rotation by acting on the pistons of the engine. The injection of air is stopped when the required rpm is detected.

This hybridization can be combined with a reduction of engine’s swept volume and makes it possible, by ensuring a good filling of cylinders, to compensate the couple variation in transient regimes as observed with an ordinary supercharging (Fig. 7). Reducing the engine’s volume while maintaining the couple and the power, results in a decrease of fuel consumption and GHG emissions. It also reduces the response time to provide an instantaneous torque as required by the charge (Fig. 7).

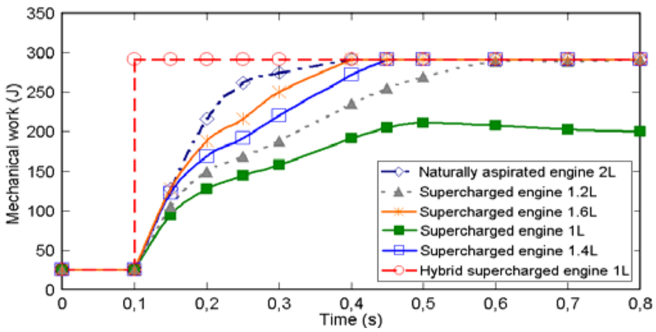

Fig. 7: Indicated work of supercharged and hybrid supercharged engines.

VII. ECONOMIC INTEREST OF WDCAS SYSTEM 1

The WDCAS has a very important commercial potential for the remote areas as is based on the use of diesel generators already in place. It is conceived like the adaptation of the existing engines at the level of the intake system, the addition of a wind power station and a compression and storage of air system. The lack of information on economics, as well as on performances and reliability data of such systems is currently the main barrier to the acceptance of the wind deployment in the remote areas. This project intends to answer some of these interrogations.

Using information available [16], [17], [18], and performance analyses [11], we estimate that on a site with good wind potential, the return on investment (ROI) for such installation is between 2 and 5 years, according to the costs of fuel transport. For sites accessible only by helicopter this ROI can be less than a year [9]. This analysis does not take into account the raising prices of fuel, nor GHG credits which do nothing but reduce the ROI.

VIII. SIMULATION RESULTS OF THE SYSTEM 1

The performance increase due to supercharging of diesel engines has been already demonstrated in many publications. For this reason, we will present only the results illustrating the advantages of the proposed design (system 1) especially for operation regimes with partial load (weak and average regime). The system is designed to provide the power required by the load using in an optimal way the hybridized air turbine with turbocharger. The analysis is based on the energy equations for the engine crankshaft and the turbo-compressor shaft. The following constraints have been added to the equations:

- The limit of air/fuel ratio in the Diesel;
- Exhaust temperature;
- The pressure of the compressed air;
- The temperature of expanded air extracted from the storage tank.

For an industrial engine having a total swept volume of 16 L (with load varying from 1500 to 2500 Nm) , the results of the analysis are presented in Figures 8 - 11.

Being given that the turbo-compressor depends strongly on the engine's rotation regime and on the applied load, it is obvious that the fuel consumption will increase with the load (Fig. 8). This will allow the turbo-compressor to function at its full efficiency and to meet the demands. The air turbine functions as an auxiliary with a weak flow and low pressure for the compressed air injected (Figs. 9, 10). On the other hand, with weak loads (weak regime), when the turbo-compressor is vulnerable (small quantity of exhaust gases, thus weak efficiency of the turbo-compressor), it is the power provided by the expansion of the compressed air in the air turbine which will assure the correct operation of the engine with a high pressure at the intake of the air turbine (20 bars) and practically same air flow. This hybridization allows its 2 main elements to play complementary roles while maintaining a high and constant pressure (10 bars) of the supercharging (Fig. 11) at the engine's intake for an important range of the load. This allows the control system to decrease the rotation regime of the engine at any moment, even for a big load, in order to decrease the fuel consumption. The decline of power and efficiency of the engine resulting from the fall of the regime will be rewarded by the supplementary power supplied by the air turbine on the turbo-compressor shaft.

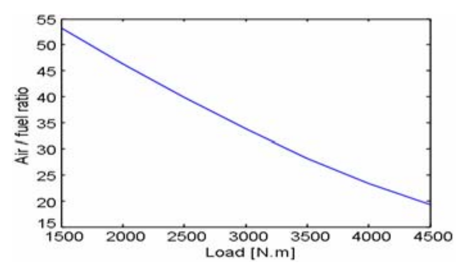

Fig. 8: Variation of the air /fuel ratio with the applied load

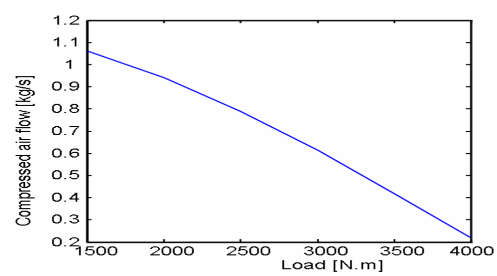

Fig. 9: Variation of the compressed air flow with the applied load.

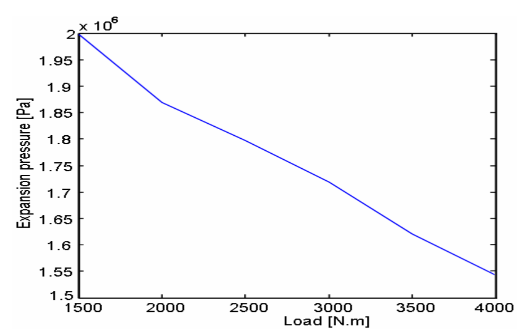

Fig. 10: Variation of expansion pressure of the air turbine with the applied load.

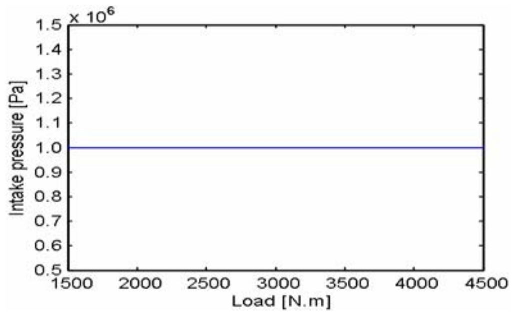

Fig. 11: Variation of intake pressure with the applied load

IX. CONCLUSION

In spite of the existence of several techniques of storage intended for applications in isolated sites (Lithium - ions batteries, hydrogen storage plus fuel cell), the proposed design remains the most effective, the least polluting, the least expensive and the most successful. Indeed, although the new batteries are more durable and more effective, they remain always expensive and require converters (AC-DC), controls systems and regular maintenance. This is without forgetting the problem of recycling at the end of their lifecycle as their limited cyclability (number of cycles) strongly depends on their depth of discharge. In the mean time, the hydrogen storage system combined with fuel cell to produce electricity, is characterized by a prohibitive price of the electrolyser and the low overall efficiency (at the best 70% for the electrolyser and 50% for the fuel cell, 35% for the set) without forgetting that the use of the hydrogen as fuel requires internal interventions on the ignition system of existing diesel engines (already in place), avoided with the proposed concept. The WDCAS allows not only increasing the penetration rate of wind energy but a fast starting up of the diesel engine. A remarkable economy of fuel, especially during the periods of low and average wind speed can be obtained by forcing the diesel to function at 25-30% instead of 50% of its nominal regime, as required by the exploiter. Indeed, the power reduction of the Diesel at lower regimes is compensated by the available power within the air turbine, which will allow maximizing the power of the compressor and improve the filling of the Diesel, its power and the efficiency. A definitive conclusion requires building and testing a prototype allowing practical validation. However, the theoretical analysis illustrates a possible application for large range of loads of this WDCAS.

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