Numerical optimization of hybrid wind-diesel system–compressed air energy storage based on genetic algorithm

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Abstract—In this study, the accessible technical ways to supercharge diesel engine in wind-diesel system with high penetration and the use of compressed air energy storage system (WDCAS) have been studied to optimize system performance and reduce consumption expenditure. The principle of the hybrid system is shown based on increasing engine performance and reducing its fuel consumption. The engine used in optimization in MATLAB software has a capacity of 5 liters and a speed of 1500 rpm. The optimization of this system has been done by genetic algorithm. Finally, the optimization problem has been raised to maximize power output as the objective function of wind-diesel system-compressed air energy storage. The obtained results of optimization show that the use of compressed air system decreases fuel consumption up to 50%.

Keywords—wind energy, diesel engine, hybrid wind-diesel system-compressed air energy storage

I. INTRODUCTION

Many isolated communities that are not connected to the national electricity network, use diesel engines for electricity production. The electricity produced by diesel engines is more expensive compared to the big electricity generating stations (gas, wind, hydro, nuclear) and more importantly, the cost of transporting fuel and environmental costs associated with this type of energy should be considered. In Quebec, Canada, almost 200,000 people live in over 300 remote communities and each area uses an autonomous diesel generator for electricity production. The electricity production in this state has caused a cost more than 50 cent/KWH in 2007 by the use of diesel generators due to the rising prices of oil products and the cost of transferring it to remote areas. However, the cost of electricity sales in other areas in Quebec available to AC power is approximately 6 cent/ KWH. So, the use of hybrid system that is a combination of renewable resources and diesel generators, reduces the fuel consumption of diesel and improves the functional costs and environmental benefits. Since the early 1980, at least 10 wind-diesel projects with low penetration were installed in different and remote regions of Canada, but only two projects have worked for more than 8 years and many other projects had a useful life of less than 2 years. Therefore, in this study the effect of applying the techniques of compressed air energy storage (CAES) on the fuel consumption of the diesel generators through numerical methods will be emphasized in order to optimize hybrid system that leads to reduce the cost of electricity production.

II. The hybrid wind-diesel system

The hybrid system should provide the energy required at any time to the extent that achieve the maximum energy from renewable sources by maintaining the quality of the output electrical energy. It is very important for the system (1) to deliver energy higher than average power of electrical generators (2) to receive the maximum energy from renewable energies. The moment capacity of wind can be estimated a maximum of 20% to 30% of the diesel engine and the total energy of wind does not exceed from 10% to 15% of electricity consumption. Although the main obstacle to achieve low fuel consumption is functional limitations of diesel generators, increasing the penetration level of wind from the low to high penetration level reduces fuel consumption. In fact, it is essential for the diesel engine to have a 30% output nominal power in standby conditions, without considering the influence of the system to be able to respond more quickly to sudden reductions in wind speed. Wind-diesel systems with high penetration, without the use of energy storage systems, are systems that the wind production power is greater than the load required for a specified period of time. This means a complete stop of diesel generators, resulting in a significant reduction of fuel consumption. On the other hand, this type of design has a complex technical problem. In systems with a medium penetration when the wind energy is reduced, diesel engine should remain in standby mode in order to give quick and early response on wind speed. This is the most important source of increased consumption.

III. Modeling system by numerical simulation

In the first step, it should be pointed out that all diesel engines that operate in remote areas are equipped with supercharged system by turbo compressor. However this
type of system loses their benefits during operation and low diet because its efficiency and performance are directly related to the amount of exhaust gas from the engine. The stored compressed air system is used in several ways to supercharge diesel engines. Various researchers have analyzed these methods in details.[1]

System 1: the use of air turbine that is directly connected to the turbocharger shaft.

System 2: the use of a two stage turbocharger.

System 3: suction of compressed air directly into the compressor.

System 4: suction of compressed air into the engine.

System 5: the use of a modified turbocharger / Hyper bar type

In this study, the proposed and accepted solution to evaluate and improve the amount of fuel used to control CAES system is the introduction of compressed air into the flow upstream in compressor. A model is considered including 5 main blocks in order to introduce and display the diesel engine. Each of these blocks corresponds to each component of the system that creates changes in the thermo dynamic state of compressed air (CA) or the burned gases out of the engine (EG). These components include air filter, compressor, heat exchanger, combustion chamber, gas turbine and diesel engine load. Each major component of diesel engines and their interactions are shown in the block diagram (figure 1).

\[ p_1 = p_0 - k_{FA} \frac{m_A^2}{\rho_0}, \quad T_1 = T_0 \left( \frac{p_1}{p_0} \right)^{\gamma - 1} \] (1)

In which \( k_{FA} \) is pressure loss coefficient on the unit square of the air filter and \( m_A \) is mass air flow.

Compressor

Understanding the properties and characteristics of the compressor is required to model system properly. Two parameters including the reduced diet and the reduced flow relate the operating conditions of the compressor to reference values \( (T_{ref}, P_{ref}) \).

These relationships are as follows [2]:

\[ \begin{cases} N_{T_{ref}}: \text{ real dist} \\ \dot{m}_{T_{ref}}: \text{ real flow} \end{cases}, \quad N_{T_{ref}} = \frac{N_{T_e}}{\sqrt{T_{ref}} \sqrt{T_e}} \] (2)

\[ \dot{m}_{T_{ref}} = \dot{m}_{T_e} \sqrt{\frac{T_{ref}}{T_e}} \] (3)

Using the characteristics of compressor, the thermodynamic parameter of air in compressor exit can be calculated from the following equations:

\[ \pi_c = \frac{P_c}{P_e^*}, \quad \eta_c = \frac{T_e}{T_{ref}} \left( \pi_c^{\frac{\gamma - 1}{\gamma}} - 1 \right) \] (4)

And ultimately the consumption of compressor is calculated as follows:

\[ P_c = \frac{1}{\pi_c^*} \dot{m}_{T_e} \cdot C_p \cdot T_0 \cdot \left( \pi_c^{\frac{\gamma - 1}{\gamma}} - 1 \right) \] (5)

In which \( \eta_c \) is efficient of the compressor, \( C_p \) is specific heat capacity of air at constant pressure and \( \pi_c^* \) is the pressure ratio of compressor.

Heat exchanger

In order to maximize the flow of air into the engine, heat exchanger reduces compressed air temperature at the outlet of the compressor. The heat exchanger is a kind of cooling air to air that performs cooling process at constant pressure \( (p_5 = p_3) \). The air temperature at the outlet of the heat exchanger \( (T_3) \) is calculated from the following equation [3]:

\[ T_3 = T_e \left( 1 - \eta_{ex} \right) + \eta_{ex} T_f \] (6)
Combustion chamber

In order to analyze the combustion chamber, the estimated amount of incoming air, the temperature of gas in engine exhaust (before entering the turbine), the flow of combustion gases and the efficiency of engine indicator are required.

Estimating the amount of incoming air to the engine and the gas temperature at the exit of it

Applying continuity equation in the size of inlet and constant collector of suction shows that the mass flow of air blown by the compressor is equal to the mass flow rate of incoming air to the \( \dot{m}_a \) engine and as follows:

\[
\dot{m}_a = \eta_r \frac{C_v}{4\pi} \omega \frac{P_a}{r_{in}} \quad (6)
\]

Here, \( C_v \) is the swept total size of the combustion chamber, \( \omega \) is the ideal gas constant, \( \omega \) is rotational speed of the diesel engine, \( \eta_r \) is volumetric efficiency of the engine and the temperature of exhaust gas can be estimated from the following equation[4]:

\[
T_a = T_e + \frac{k}{\lambda} \quad (7)
\]

In which, \( \lambda = \frac{\dot{m}_a}{\dot{m}_f} \) is the ratio of air to fuel and \( k \) is a constant number that is obtained experimentally.

Estimating the efficiency of the engine indicator

As long as the engine runs with a constant speed and also with consideration of the physical limitations of combustion, the second-class relationship is created as follows [5]:

\[
\eta_f = \alpha + b\lambda + c\lambda^2 \quad \text{if} \lambda \geq \lambda_{opt}
\]

\[
\eta_f = (\alpha + b\lambda + c\lambda^2) \frac{\lambda}{\lambda_{opt}} \quad \text{if} \lambda < \lambda_{opt} \quad (8)
\]

Gas turbine

In this study, turbine has been considered with fixed geometry. Flow changes reduce and \( \dot{m}_{rt} \) can be approximated by a third-degree polynomial curve to the point of curvature with the rate of expansion \( \Pi_t \) that is completely independent of the rotational flow diet.

\[
\dot{m}_{rt} = \left\{ \begin{array}{ll}
\alpha + \Pi_t^2 + b, \Pi_t^2 + c, \Pi_t + d & \text{if} \Pi_t \leq \frac{\pi}{2a} \\
-cd - \frac{b}{2\pi^2} + \frac{b}{2\pi} & \text{if} \Pi_t > \frac{-\pi}{2a}
\end{array} \right. \quad (9)
\]

IV. Optimization of wind-diesel system – compressed air energy storage

Wind - diesel system – compressed air energy storage provides the power and strength needed to load while it achieves force from hybrid system. This means that the use of productivity both in gas and air turbine in improving the flow of incoming air to the diesel engine. Consequently, in order to maximize the power of the compressor as the objective function the optimization problem is proposed. Wind power is not considered in optimization problem because modifications are only applicable in diesel engine. A set of constraints should be defined as equal or unequal, like any other optimization problem[6]. If the power of compressor is maximized it will be essential to balance between the engine energy with itself and turbocharger system.

Optimization can be stated as follows:

\[
\text{Maximize } P_c = \frac{1}{\eta_r} \dot{m}_a \cdot C_p \cdot T_e \cdot \left( \frac{\Pi_{c}^2 - 1}{2} \right) \quad (10)
\]

Equality constraints used in the optimization of this system are:

Equation of the motor shaft:

\[
P_m - P_f = 0 \quad (11)
\]

\[
P_m = \left( 0.87 + 0.18 \frac{N}{1000} - 0.06 \left( \frac{N}{1000} \right)^2 \right) \frac{C_p}{4\pi} \omega - C_p \omega = 0
\]

Equation of the turbocharger shaft:

\[
P_t - P_f - P_f = 0 \quad (12)
\]

\[
\eta_r \cdot \dot{m}_a \cdot C_p \cdot T_e \left( \frac{\Pi_{c}^2 - 1}{2} \right) \eta_r - \dot{m}_a \left( 1 + \frac{\Pi_{c}^2 - 1}{2} \right) \eta_r \cdot T_e \left( 1 - \frac{\Pi_{c}^2 - 1}{2} \right) \eta_r = 0
\]

Inequality constraints used in the optimization of this system are:

.Limitation of air-fuel ratio in diesel engine as follows:

\[
15 < \lambda = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} < 80 \quad (13)
\]

The temperature of outlet combustion gases has limitation as follows:

\[
T_e < T_{exhaust \ limit} = 900K \quad (14)
\]

The pressure of compressed air has the following limitation:
If each phrase is replaced with the amount of its constraints, inequality constraints will be considered as follows:

Limitation of air-fuel ratio in a diesel engine:

\[ p_{\text{air}} = 1 \text{bar} \leq p_{\text{in}} \leq p_{\text{max}} = 80 \text{bar} \] (15)

Limitation of the temperature of outlet combustion gases:

\[ T_3 + \frac{K'}{1 + \frac{K'}{1}} = 1200 \text{K} \leq \beta \] (16)

In which \( K' \) is a constant value and equal to 1200 K.

Compressed air pressure has also a limitation as follows:

\[ p_{\text{at}} = 10 \leq 0.1 - p_{\text{at}} \leq 0 \] (18)

V. The obtained results of optimization

In the study, the used engine in optimization in MATLAB software has a capacity of 5 liters and a speed of 1500 rpm. Here, we have used the information as given equations or made interpolation into the problem solving. Therefore, the results of the optimization have been provided using genetic algorithm in figures (2) to (5). Figure (2) shows inlet pressure required to the compressor in order to the engine at its maximum efficiency in the use of compressed air storage system. In fact, due to the lack of use of the CAES system, the inlet pressure of compressor is constant and equal to 1. CAES system feeds compressor in the pressure required to fulfill the exact flow of air required to the performance (efficiency) of maximum engine (air-fuel ratio is equal to 53). In this study, the pressure is variable between 1 bar at too low rotational speeds and 2.6 bar at full load.

Figure 3 shows the ratio of pressure (density) in turbocharger compressor with and without the use of compressed air energy storage system. Using the CAES, the flow of fresh air that passes through the compressor is increased and therefore the pressure ratio when CAES system is not used, decreases. Consequently, with using the CAES, compression ratio of turbocharger is reduced and it decreases the consumption of turbocharger.

Figure (4) shows the expansion ratio of gas turbine with and without the use of compressed air. If we use compressed air energy storage system, the expansions ratio increases in contrast to the lack of using CAES system due to increasing in the flow exhaust gases passing through the turbine. As a result, the expansion ratio of turbocharger turbine increases in the case of using CAES system and this will lead to increase in production of turbocharger.
Finally, figure (5) shows the reduction in consumption fuel that is a result of using compressor air energy storage system. The reduction in consumption fuel continues by increasing the load to its peak value till 50% of the fuel in the load of 800 Nm will be saved. as the figure shows, an increase in fuel consumption will be remarkable in the lack of using CAES from the load of 2000Nm the top.

VI. Conclusion and summary

We have investigated the effect of compressed air energy storage on the amount of fuel consumption of diesel engine by numerical methods. Here several components of system such as air filter, compressor, heat exchangers, combustion chamber, gas turbine, and motor loads in MATLAB software have been coded, modeled and simulated. Considering the purpose of this study that is to evaluate the improvement of fuel consumption in diesel engine that works with $\lambda = \lambda_{opt}$. We have simplified the problem assuming that the compressed air supplies the compensating pressure required to the incoming air filter till the air works with $\lambda = \lambda_{opt}$ even when the atmospheric pressure is not sufficient. In this study, the used engine in optimization in MATLAB software has a capacity of 5 liters and the speed of 1500 rpm. The optimization of this system has been done by genetic Algorithm. Finally, in order to maximize the output power as an objective function of wind-diesel system compressed air energy storage, the optimization problem has been considered because changes is applicable in diesel engine and finally it has been shown that fuel consumption can be reduced up to 50%.

References


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