Compressed Air Generator for Low Wind Speed Electrification

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Abstract

The objective of this paper is to present a compressed air generator (CAG) that designs for low wind speed electrification application. The CAG is a reciprocating machine operated with low pressure of compressed air that works as an expansion air engine. It transforms the compressed air power to the electrical power via the expansion air engine coupling with an induction machine for electrification. The CAG is not like the conventional machine, which use the fuel fossil for internal combustion, therefore, it don't generate air pollution that is the main problem in environment. The CAG prototype is designed with the local contents in THAILAND, which consists of four cylinders operating alternatively with air pressurize. The engine is modified from standard TOYOTA engine and controlled by an electronics controller unit, which produces the on-off control signal for solenoid valves as the charging-discharging valves to supply the air pressurize to machine. The experimental result shows the system design, investigates the characteristic of CAG prototype and presents all of machine efficiency. The system was tested under a range of expansion pressure ratios in order to determine its characteristics and performance. At the operational pressure of 5 bar, the efficiency of expansion air of 49.34% is calculated, while the efficiency of generator of 60.85% is examined. The overall efficiency of system of approximately 30% is also investigated.

Keywords: Compressed Air Generator, Expansion Air Engine, Compressed Air Energy, Compressed Air Electrification, Wind Energy.

Introduction

Wind energy assessment of Thailand is educated by the department of energy development and promotion (DEDP) that depicted and estimated distribution of wind resources at 10m, 30m and 50m height. The assessment indicates that Thailand have good wind energy potential areas by average wind speed is 6.4 m/s at 50m height cover area approximate 20%. Nevertheless, around 80% of area in Thailand has average wind speed varying from 2.5 m/s resulting to not appropriate in electric generation. The optimum of wind energy potential in electric generation is 4 m/s or higher, generally. From all information express that Thailand has low wind speed, fluctuate and not stable. It is not reliable energy source since the power cannot produce all the time. Thus, the appropriate technology of wind electric generation for Thailand is needed for solving their problems, which the energy storage systems are considered as a key technology. There are many types of energy storage, including batteries, flywheels, ultracapacitors, superconducting magnetic energy storage, flow batteries, pumped hydroelectric energy storage (PHES), and compressed air energy storage (CAES). CAES, which are long service period, low cost of energy, low cost of maintenance and operation and high power efficiency [1], have been demonstrated as economically solutions for utility-scale energy storage on the hour time scale. This system have successfully implemented in Hantorf in Germany, McIntosh in Alabama, Norton in Ohio, a municipality in Iowa, in Japan and under construction in Israel [2]. The CAES produces power by storing energy in the form of compressed air in an underground cavern. An air is compressed during off-peak periods, and is used on demand during the peak periods to generate power with a turbo-generator/gas turbine system. However, this system seems to be disadvantage as it is quite large power facility and is needed large underground carven, while having a limitation in terms of site installation.

The CAES is mostly applied on the hybrid energy storage system, such as those based on CAES and super-capacitor energy storage with a maximum efficiency point tracking (MEPT) algorithms [3], base on CAES, thermal storage and flywheel energy storage [4], based on CAES and combustion turbine (CAES-CT), this approach will reduce the energy consumption and increasing efficiency of a system by integration of the renewable energy source [5], based on wind-diesel system and CAES (WDCAES), this design leads to the increase of diesel power and efficiency, to the reduction of fuel consumption and GHG emissions, in addition to economics on the maintenance and replacement cost of the diesels [6] also based on CAES and thermal storage for UPS and load leveling in conjunction with wind or solar energy generation to improve cycle efficiency for electricity storage [7]. The last CAES application is the transportable compressed air energy storage (T-CAES) system. It consists of 2.5 MW of wind turbine, the logic circuit for input power acceptance, a 500 kW electric motor, compressor, and turbo-expander/generator, storage tank and power conditioner. The output of this system is electrical power and chilled air obtained in expansion processes. The disadvantage of this system works at high wind speed since the system needs the electrical power from wind turbine for driven compressor to produce the compressed air. Some 2.1-inch thick tanks can be used for storing the compressed air under high pressure but it is required special order for their production. The cost is also high [2]. The most popular applications of CAES are cost reductions, decreased energy consumption and increased system efficiency. Nevertheless, they use turbine expansion, which is combustion turbine and non-combustion expander, to produce electricity in MW rated power. They do not focus in a small renewable power plant for poor or medium performance area to improve renewable energy assessment in the country such as Thailand. Therefore, a small-scale renewable electrical generation has attracted new attention, which has the advantages of distributed electric energy generation.

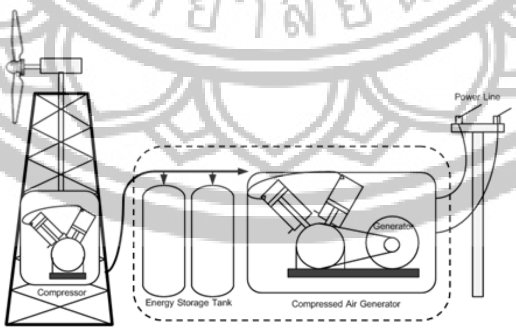


Figure 1 The proposed system of low wind speed electrification base on CAES

In this paper presents the low wind speed electrification system based on CAES, which shows in figure 1, by using the compressed air generator. This system is a hybrid technology of the energy storage and the electrical power generation. The energy will transfer to the CAES system by using the multi-blade wind turbine coupling with air compressor, which produces high-pressure compressed air at ambient temperature. It is stored in above ground pressure storage tank as a temporary storage. It will be supplied to engine to drive a shaft coupling with a generator to electrification when we need. Then, electrical power is conversed by grid connected inverter, which is synchronized at distribution line. In this paper will focus in dash line box for doing experiment of CAG system to obtain the characteristic and performance, which can helpful in system designing.

Compressed Air Generator

Thermodynamics of Compressed Air Expansion Engine

The compressed air expansion engine is mechanical prime mover of electrical generator powered by the compressed air in storage tank. Then, the potential energy from vessel will be transformed to mechanical energy on the shaft of engine by opening the solenoid valve that control four cylinders operating alternately. Therefore, it has four thermodynamic cycles that the same. The full cycle is completed within one revolution for a four-stoke cycle. The engine composes of four steps: charging, discharging or expansion and exhausting, which displays the P-V diagram in figure 2

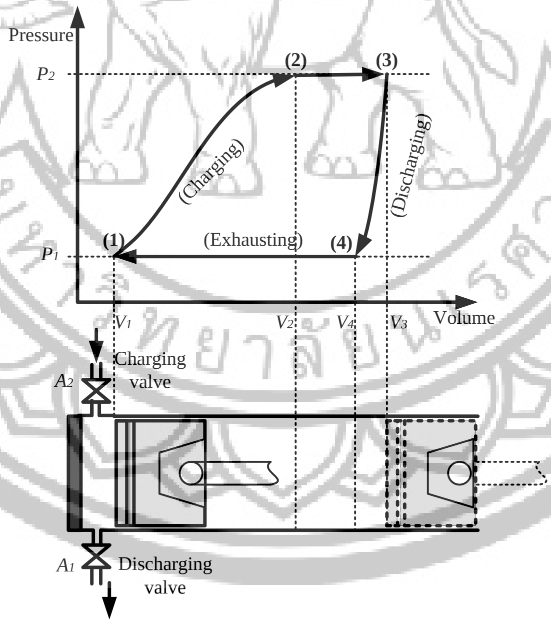


Figure 2 P-V diagram of air expansion engine operation

The work of the air expansion engine cycle can be continuously varied by adapting the timing of the charging and discharging valve closure. The enclosed area *(1)-(2)-(3)-(4)-(1)* measures the net work done upon the piston during the air expansion engine cycle by the compressed air. The total work done by the compressed air during the processes of the cycle amounts to:

$$Total\ \ work(W_{net}) = W_{charging} + W_{Discharging} + W_{exhausting}$$

or

$$W_{net} = (\int_{V_1}^{V_2} PdV + \int_{V_2}^{V_3} PdV) + \int_{V_3}^{V_4} PdV + \int_{V_4}^{V_1} PdV$$

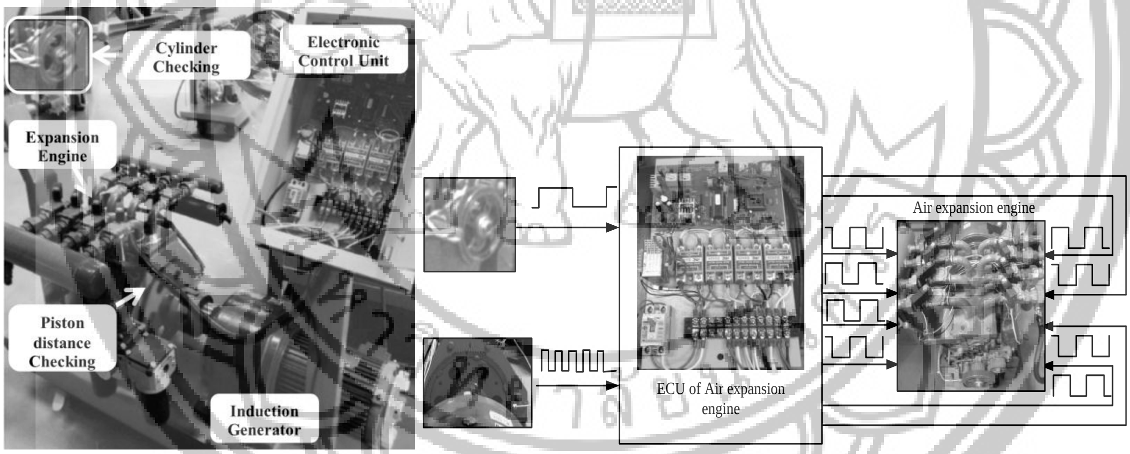
Applying Equations (1) - (4):

$$W_{net} = \left[\frac{1}{2}(P_2+P_1)(V_2-V_1)\right] + \left[P_2(V_3-V_2)\right] + \left[\frac{1}{2}(P_1+P_2)(V_4-V_3)\right] + \left[P_1(V_1-V_4)\right] \quad (5)$$

In equation (5), the work is for 1 stroke, therefore, the total work of the air expansion engine for 1 cycle is 4 times of W_{net}.

Compressed Air Expansion Engine Development

The air expansion engine is designed with the local contents that apply a Toyota engine model 4k, 1290 cc, 60 hp (45 kW) at 5,250 RPM. It consists of 4 cylinders with bore 7.5 cm and stroke 7.3 cm thus, the cross section area is 44.18 cm^2 and cylinder volume is 322.50 cm^3. The shaft of engine directly coupled with the generator passes through the pulley transmission in ratio 1:40 resulting in the generator turn over the synchronous speed, therefore, it consume the compressed air around 51.6 liter per minute. On the other hand, if an air motor turbine is used it will consume the compressed air around four times of piston engine or around 2,000 liter per minute. Thus, the standard Toyota piston engine is chosen in this work. Show the configuration of compressed air engine in figure 3(a).



(a) (b)

Figure 3 (a) Compressed air generator configuration and (b) Control system configuration

Compressed air electrification depends on expansion pressure operation corresponding to solenoid valve controlling. The operation is controlled compressed air supply by on-off solenoid valves, which are controlled by an electronics controller unit that like an ECU box of the general car engine. For power investigation, CAG ability to produce mechanical power is

$$P_E = \frac{T*2\pi N_E}{60*1,000}\ \ kW \quad (6)$$

And

$$T = P*\frac{\pi D^2}{4}*\frac{stroke}{2}\ \ N.m.$$

The expansion power is the function of the expansion work and the speed of the expansion air engine N_E resulting to the expansion power is directly dependent on the operating pressure and the speed of the expansion air engine.

$$P_E = f(P, N_E)$$

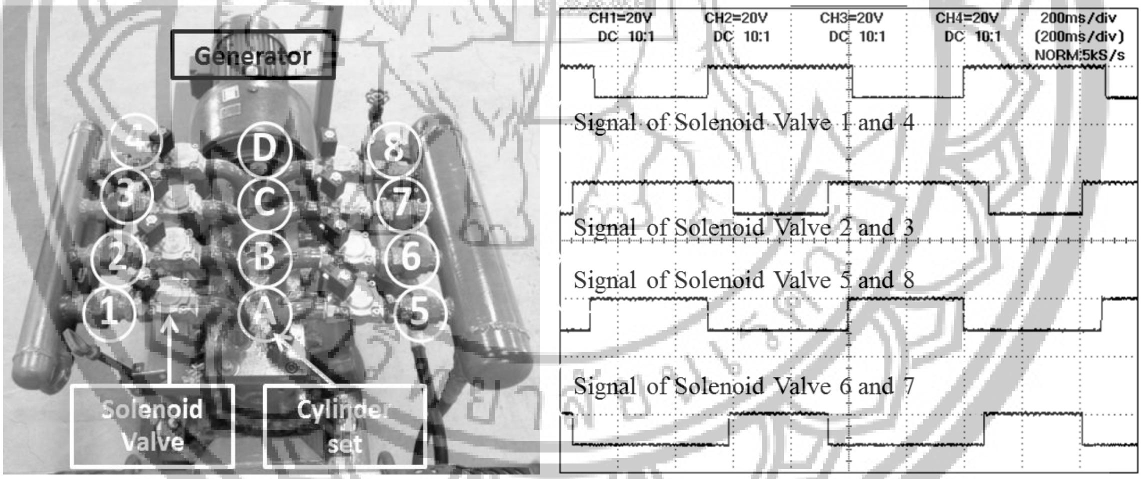
The corresponding of the mechanical torque that is the function of the expansion power and the speed as:

$$T = f(\frac{P_E}{N_E})$$

Therefore, the torque is the function of the operating pressure ($T = f(P)$). The efficiency is

$$\eta = \frac{P_E}{W_{net} * N_E} * 100\% \qquad (7)$$

Where P_E is power in watt(W), T is torque in newton-mater(N.m), N_E is mechanical speed in revolution per minute (RPM), P is operation pressure in pascal(PA), D is cylinder diameter in meter(m)and η is efficiency. The command in control is produced from checking cylinder number and position of piston by induction proximity sensors. Then, ECU will evaluate and produce pulse on-off signal to control solenoid valve. The electronic control unit uses the data from two sensors: cylinder checking and piston distance checking to compute the period time to control the eight solenoid valves. The system block diagram shows in figure 3(b).



(a) (b)

Figure 4 (a) Position of valve and cylinders and (b) Solenoid valve control signals

Figure 4 shows the position of valve and cylinders and the solenoid valve control signals. The first half cycle to expand the volume of cylinder *A* and *D*, the solenoid valves (1), (4), (6) and (7) will operate together but the time in operation is different, one as input and the other as exhaust, which works differently in the cylinder. The solenoid valves (1) and (4) control compressed air into the cylinder *A* and *D*, and the solenoid valves (6) and (7) control the exhaust air at the cylinder *B* and *C*. The solenoid valves (6) and (7) operate longer than the solenoid valves (1) and (4) for the ten pulses of piston position sensing to avoid the resistance of the pressure between the cylinders. Moreover, every time that the input valves ((1),(2),(3) and (4)) open to supply the compressed air into the cylinders, they have to wait for the position of the piston sensing for six pulses to provide an area of the cylinder resulting in the air engine operating smoothly. The second half cycle, the solenoid valves (2) and (3) as the input valves and (5) and (8) as the exhaust valves will be opened, resulting in the volume in cylinders *B* and *C* expanding. The expansion engine turns completely cycle. The shaft of the expansion air engine directly coupled with the generator passes through the pulley transmission in ratio 1:40 resulting in the generator turn over the synchronous speed. Consequently, the generator produces the electrical power.

In electrical generation process, the generator will operate in variable speed by using the power converter that is connected between generator and power line distribution. The power converter works for two modes, namely, rectifier and inverter mode. The rectifier mode operates when the asynchronous machine is generator. It converts the alternating current (AC) to the direct current (DC). An inverter mode operates same as a static VAR for excite the magnetizing current. The Grid Connected Converter is used to invert from DC to AC in order to connect with the power line as well as control the constant voltage and the frequency. In addition, the power quality is controlled in this section.

Experiment and Result

This experiment will connect the compressed air generator and the grid-connected inverter in order to investigate the behavior of the expansion air engine generating electric energy enforce to the distribution line. The electric energy, which is generated in good quality: pure sinusoidal with frequency 50 Hz, a unity power factor and low harmonic distortion, is not the electrical pollution in the distribution line. The experiment is set up in figure 5.

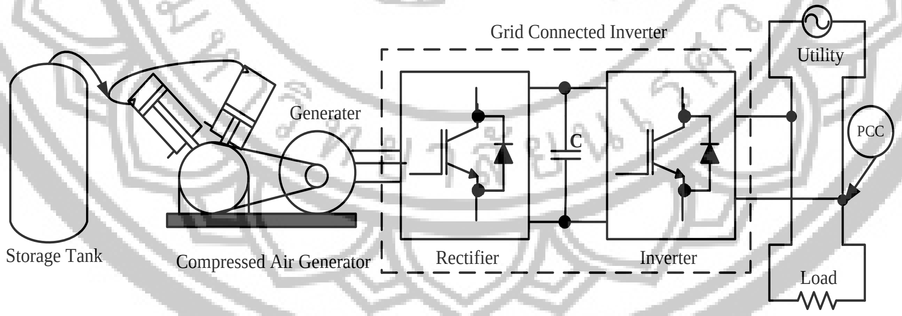


Figure 5 Experiment configuration of the compressed air electrification

The input signal, which use for executing command to control is shown in figure 6. This picture shows the solenoid valve driving signals, the pressure in the cylinder and the position of the piston that monitor only in the cylinder *A* to analysis the behaviour of the engine. However, we assume that it has the same characteristic with other cylinders.

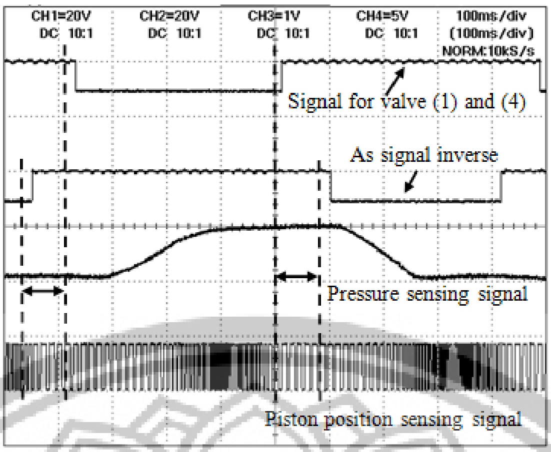


Figure 6 Relationship of the solenoid driving, the pressure in the cylinder and the piston position signals.

Figure 7 presents the mechanical power and the speed relation of an expansion air engine as a prime mover under the operating pressure change. We can see that the engine speed directly depends on the operation pressure change. From torque function, that corresponding with the operating pressure $(T = f(P))$ therefore the mechanical torque of engine is directly depend on the speed of air engine. This is mean, the speed of a prime mover increase in order to the system produces the electric power increase, too.

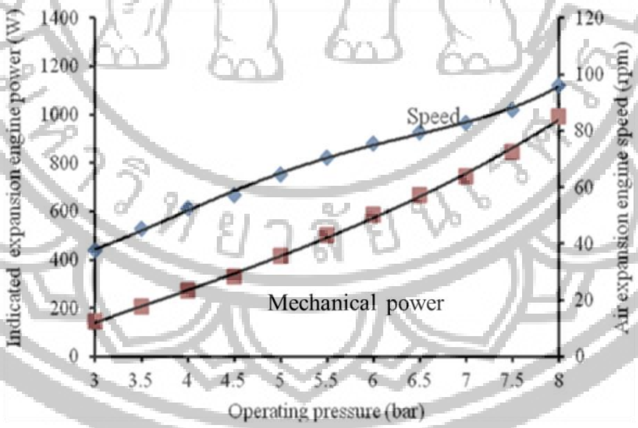


Figure 7 The mechanical power and speed relationship of under the operating pressure change

Figure 8 presents the relationship of the power components in the system and the operating pressure change. The components of the power in the system is composed of three segments. One is the power of the compressed air that is the input energy enter to drive the pistons of the engine by using a pressurize air. Second is the indicated mechanical power, which transfers from the compressed air power via the expansion air engine. The last is the electrical power that transfers from the mechanical power via a generator. The all powers will increase following the input pressurize air increasing resulting to the air expansion engine consumes the compressed air increasing as the electrical and mechanical power production.

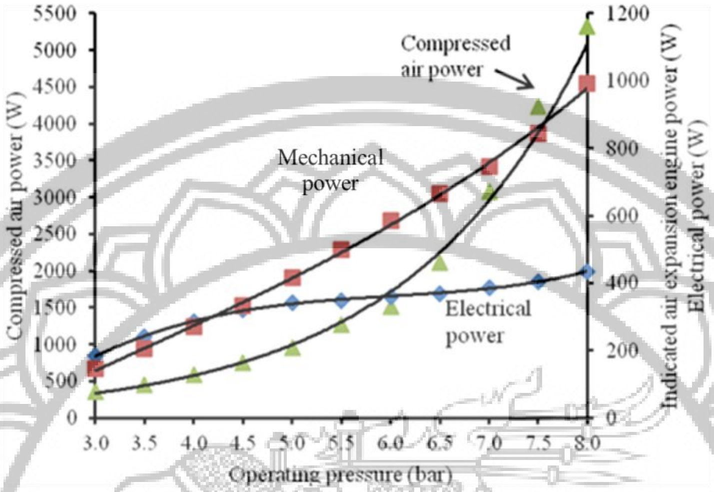


Figure 8 The relationship of the power components in the system and the operating pressure

Then the experiment connects the compressed air generator with the grid-connected inverter in order to investigate the behavior the electric energy enforce to the distribution line. The experimental results that compare the inverter voltage and the grid voltage before and after synchronize to the utility shown in figure 9. We can see that the inverter voltage is enforced to follow the grid voltage and the waveform of the voltage and the current are purely sine wave resulting to the harmonic of them are minimal when compare with before synchronize. Therefore, this compressed air generator system can produce and enforce the electric power to the distribution line. The voltage almost constant have average 220.8 volt. The current will increase following as the operating pressure resulting to the power adds, too. The efficiency at the grid-connected inverter is average 95.4%. The relationship of the efficiency of the whole of the system is presented in figure 10, which the overall efficiency decreases the operating pressure increases because of thermodynamic loss in expansion that the temperature between input and output in operation is much difference. Moreover, mechanical loss adds, when the CAG speed boosts. Therefore, the optimum operating pressure that depends on speed and torque of generator is important for system design which will be suggested in the future work.

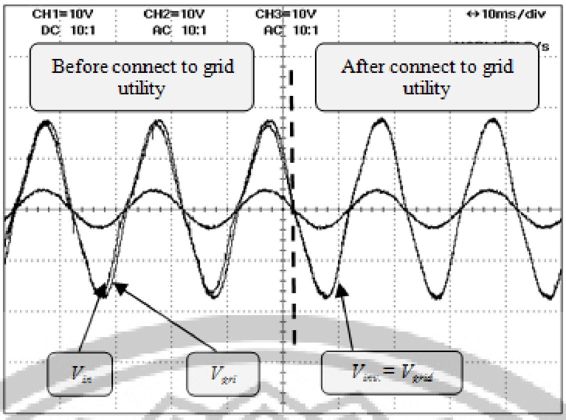


Figure 9 Comparison of the inverter voltage and the grid voltage before and after synchronizing to the utility

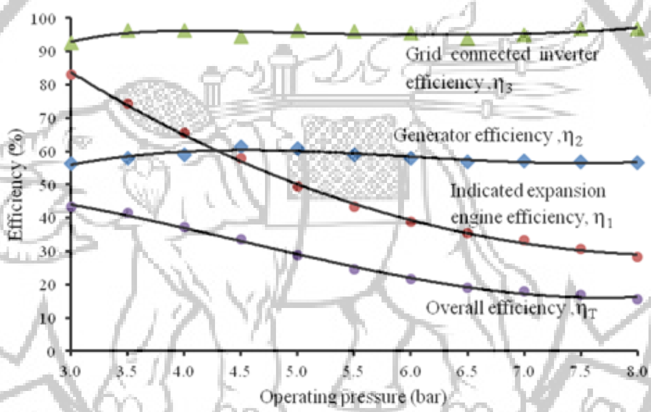


Figure 10 The relationship of the efficiency of the compressed air engine generator connecting grid inverter

The power transfer of the compressed power to electrical power indicates in figure 11 is a significant example. At the operational pressure of 5 bar, the engine turns 64.5 rpm with a torque of 83 N.m. Here, the compressed air power of 1,136.52 W is estimated. The mechanical power of 560.78 W is also calculated. In addition, the electrical power of 341.25 W is eventually estimated. Based on the power transfer shown in figure 11, the efficiency of expansion air engine (η_1), that is defined by electrical power output divided by compressed air power, of 49.34% is investigated, while the efficiency of generator (η_2) of 60.85% is examined. Here we can see that the overall efficiency of system is approximately 30%.

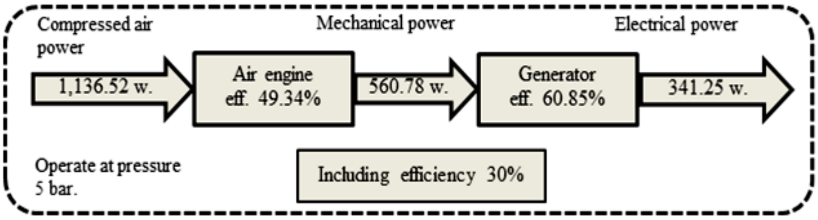


Figure 11 Power transfer from compressed air power to electrical power

Conclusion

The research has shown that the compressed air generator system for the low wind speeds characteristics of the Thailand climate, which cannot drive large wind turbines having high cut in speeds, can be harnessed with multi-blade wind machines storing energy as air compressed into cylinders. The compressed air can then be used to drive air expansion engines, which in turn drive electrical generators. The new concept of directly converting the wind energy to pressurized air will be developed as a small unit installed above ground to avoid the site limitation with underground large scale compressed air storage system. Therefore, it is suitable to be placed at any location in Thailand. The significant results showed that compressed air power of 1,136.52 W is estimated, while the mechanical power of 560.78 W is calculated. The electrical power of 341.25 W is also estimated. In addition, the efficiency of expansion air of 49.34% is calculated, while the efficiency of generator of 60.85% is examined. The overall efficiency of system of approximately 30% is also investigated. The experiment results are satisfied with performance and efficiency that can be used for prototype to study. It is feasibility for real implementation as prime mover of electrical generator. Furthermore, CAG is absolutely no fuel required and no combustion resulting to no generate heat and air pollution. Therefore, it is friendly environment and solves the energy crisis in present. This study can be helpful in system designing for the renewable energy applications, which can use the local available contents resulting to low initial cost. The proposed system can apply to uninterruptible power supply, peak shaving for the energy building management, pneumatic application and air power vehicle (APV).

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