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Small-scale compressed air energy storage systems with maximum efficiency or power tracking

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Abstract

In this study, we focus on power monitoring and optimum efficiency for a small-scale compressed air energy storage system's electric generator that is operated by pneumatics. A resistive load is used to regulate the output power of a permanent magnet DC generator driven by an air motor. The buck converter provides regulated power at its output, allowing the air motor to run at a speed that optimizes for either power production or efficiency. The maximum point tracking controller employs an inherent control action and a linearized model of the air motor. Small injected-absorbed current signal-model of the buck converter is used for analysis and construction of the controller. Experiments were conducted utilizing a dSPACE system to create the controller. The design's validity and capabilities are shown by presenting test results.

Introduction

Figure 1 depicts a small-scale compressed air energy storage (CAES) system, which has the potential to serve as an alternative energy storage system for renewable sources [1-4]. The energy density and efficiency of these batteries are lower than those of lithium batteries, but they have the benefit of being safer for the environment. Recent studies [1, 2] have focused on optimizing the discharging process using a technique called maximum efficiency point tracking (MEPT). Maximum power is often achieved at a speed different from the air motor's maximum efficiency, necessitating the employment of a maximum power point tracking (MEPT) technique.

Both the MEPT and MPPT designs for the CAES seen in Fig. 1 are discussed in this work. A permanent magnet DC generator is powered by an air motor in this setup. In order to accomplish either maximum efficiency power transfer or maximum power point tracking, a buck converter regulates the DC generator's output power.

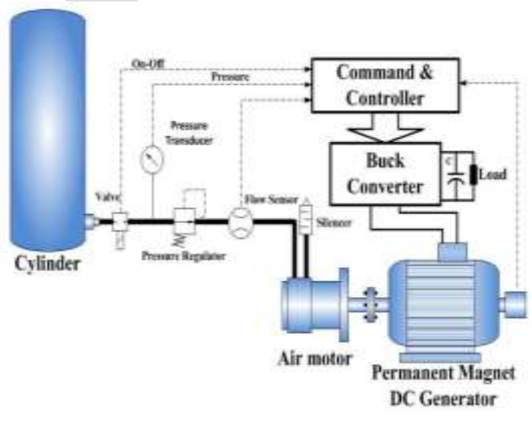

Fig. 1. Configuration of the proposed discharging process with MEPT/MPPT strategies

Using a modified version of the previously established curve fit equations for an air motor's air

consumption [1] and an appropriately adapted model for a buck converter with a PM DC generator, the study first details the modelling of a pneumatic to electrical energy conversion. Using a linearized model of the air motor and a small-signal model of the buck, we examine the system's stability. Finally, the study shows experimental data and examines the controller's practical use.

Structured Model

We then create a model of the system by deriving linearized models of the air motor and buck converter.

Model of an Air-Powered Motor

The LZB 14 AR034 (100W) air motor[5] is used here with a varying intake pressure (pi). We may use the following equations to describe the motor in terms of its torque (Mm), power (Pm), and air consumption (V a):

$$M_m = M_o(p_i)\left(1 - \frac{N_r}{N_o(p_i)}\right)$$

$$P_m = M_o(p_i)\frac{\pi}{30}\left(N_r - \frac{N_r^2}{N_o(p_i)}\right)$$

$$\dot{V}_a = \dot{V}_{\max}(p_i)\exp\left(-\left(\frac{(N_r - c_1)}{c_2}\right)^2\right)$$

In these equations, the stall torque is Mo (pi) = ct1·pi +ct2, the free speed is No (pi) = cn1pi 2 +cn2·pi +cn3, and the maximum air consumption is V̇ max(pi)= ca1·pi + ca2 , where, ct1, ct2, cn1, cn2, cn3, ca1 and ca2 are real constants determined using curve fitting of the performance curves of the motor shown in Fig. 2. The maximum efficiency and maximum power lines clearly occur at different speeds as illustrated in Fig. 2. They are also strongly dependent on pressure.

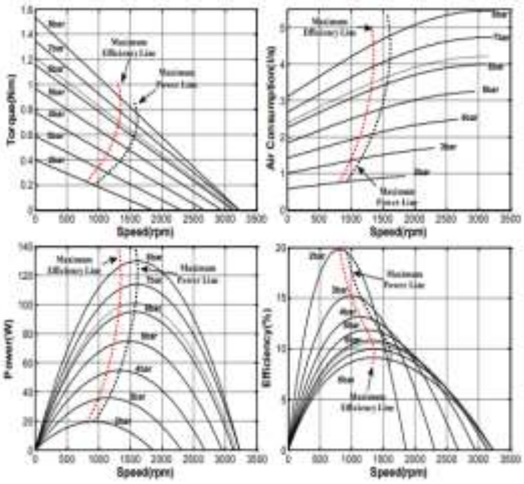

Fig. 2. Maximum efficiency and power lines on air motor characteristic curves

The derivative of shaft power of air motor (Pm) with respect to speed change is as below:

$$\frac{dP_m}{dN_r} = M_o(p_i)\frac{\pi}{30}\left(1 - 2\frac{N_r}{N_o(p_i)}\right)$$

Equating the above derivative to zero we obtain

$$N_r = \frac{N_o(p_i)}{2}$$

when the output power of the air motor is maximum. The conversion efficiency of the air motor (Kpm) can be shown to be given by the ratio of the shaft power to the expanded air power at isentropic conditions[1],

$$\eta_{pm} = \frac{M_a(p_i)\frac{\pi}{30}\left(N_r - \frac{N_r^2}{N_o(p_i)}\right)}{\frac{\gamma}{\gamma-1}p_a\dot{V}_a\left[\left(\frac{p_i}{p_a}\right)^{\frac{\gamma-1}{\gamma}}-1\right]}$$

The derivative of the conversion efficiency in (6) can be expressed as

$$e = \frac{d\eta_{pm}}{dN_r} = K_1(1-K_2N_r)$$

where the K1 and K2 are defined as:

$$K_1 = \frac{M_a(p_i)\frac{\pi}{30}}{\frac{\gamma}{\gamma-1}p_a\dot{V}_a\left[\left(\frac{p_i}{p_a}\right)^{\frac{\gamma-1}{\gamma}}-1\right]} \quad \text{and} \quad K_2 = \frac{2}{N_o(p_i)}$$

In the frequency domain (7) will be transformed to:

$$sE(s) = K_1U(s) - K_1K_2N_r(s)$$

The Maximum Point Controller

The MEPT/MPPT controller is shown in Fig. 5. The user can select either MPPT or MEPT. When the MPPT is selected, the speed reference of the regulator is set to be half the free speed for the measured pressure according to equation (5). When the MEPT is selected, the reference speed is set such that the derivative of the efficiency is calculated using equations (7) and (8).

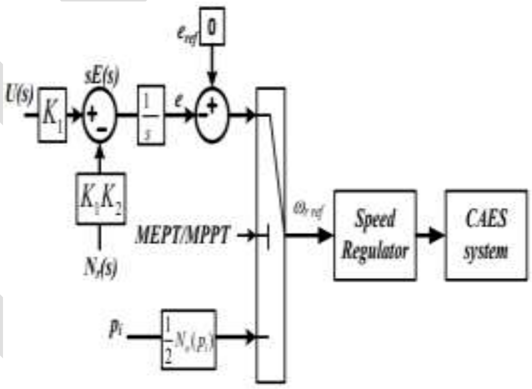

Fig. 5. The MEPT/MPPT controller

The reference speed is used to set the duty cycle of the buck converter as shown in Fig. 6. The speed regulator has 3 feedback loops of the actual speed, buck inductor current and the load voltage.

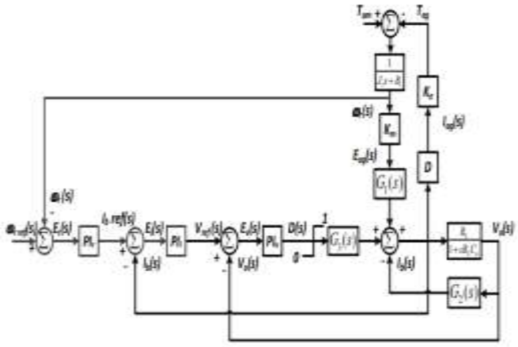

Fig. 6. The speed regulator controller

Experimental Implementation and Results

The proposed discharging process with MEPT/MPPT strategies in stand-alone was implemented using a dSPACE MicroAutobox II System that can be programmed graphically using MATLAB-Simulink. The PM DC generator used was a LEMAC/65167-008, (24V, 3000 rpm, 250 W). An Atlas Copco LZB 14 AR034 (100W) was directly coupled to the generator. Data from the speed sensor, pressure transducer and flow sensor were sampled at a frequency of 20 kHz. A 100 VA the buck converter used a MOSFET switching at 10 kHz. The load resistance RL was nominally 0.25 :, but it can be switched to have that value during the test. The systems parameters are shown in Table 1.

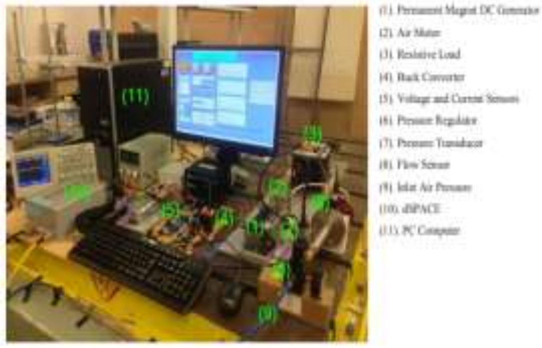

Fig. 7. Experimental rig in discharging process with MEPT/MPPT strategies in stand-alone system.

The results in Fig. 8 show the response of the system under different load conditions for both MEPT and MPPT modes of operation. It is clear that the reference speed needed to achieve maximum efficiency is different from that needed to achieve maximum power. The results also show that the system is capable of coping with variable load conditions. Fig. 9 shows good agreement between the theoretical and experimental maximum power and maximum efficiency operating lines.

Table 1. System parameter values.

Description	Symbol	Value
Armature resistance	r_{ag}	0.484 Ω
Inductance of the generator	L_{ag}	585 μH
Torque and speed constant	K_e , K_m	0.086
Total moments of inertia	J_t	0.001125 kg.m^2
Viscous friction coefficients	B_t	0.001144 Nm s/rad
Inductance of the buck converter[7]	L_{buck}	157 μH
Capacitor of the buck converter[7]	C_o	11 μF
Atmospheric pressure	P_a	10^5 Pa
Ratio of specific heat	γ	1.4

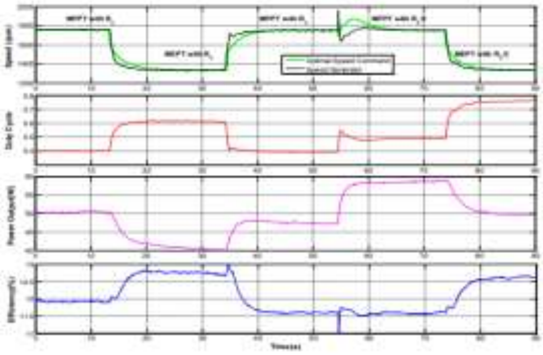

Fig. 8. Response of the system under MPPT and MEPT strategies with different load at constant inlet pressure of 6 bar

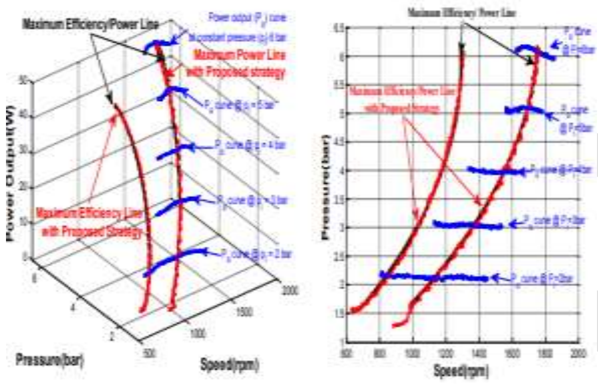

Fig. 9. Experimental and theoretical maximum power and maximum efficiency operating lines

Conclusion

Maximum power may be monitored by setting the air motor's reference speed at half the free speed at a certain pressure. Motor parameters and measurement of speed and pressure may also be used to determine the speed of an air motor that yields optimal efficiency. These methods were shown effective in experimental settings. These methods, however, need the use of speed and pressure sensors in addition to rigorous characterization of the air motor. Alternative methodologies that don't need air motor characterisation and employ fewer sensors will be investigated in future study.

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