Modeling And Study of Stirling engine connected with electric generator for Energy Harvesting of PDSs

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Abstract
As concentrated dish (CSP) using Stirling engines (SEs) become more dominant as a renewable and usage power source. Importance of model and simulating these systems is growing to study its performance under different operating states. In this study, for contributing (CSP) energy harvesting studies, we implemented a Stirling engine simulation block connected with an electrical generator which controlled by a PID controller under MATLAB/SIMULINK. It models and study the thermomechanical performance of SE and electric generator. The model's domain extends from the solar energy (constant temperature in our model) to thermal, mechanical, and output electrical energy, helping to study system relations through subsystems. It is a non-linear model, that utilized to study transient and dynamic phenomena, and a complete system operation process can be simulated, from start-up to full power state. The detailed model and simulation results are discussed in this paper. It can be said that there are no helpful components for SE modeling studies, and the present literature studies are developed for special systems not for general purposes.

Keywords: CSP; Stirling engine; Electric generator; Rectifier; PID controller.

الملخص:

نظرًا لأن الطبق المركز (CSD) الذي يستخدم محركات "ستيرلنغ" يصبح أكثر انتشارًا كمصدر للطاقة المتجددة والاستخدام .تتزايد أهمية النموذج ومحاكاة هذه الأنظمة لدراسة أدائها في ظل حالات التشغيل المختلفة .في هذه الدراسة، للمساهمة في دراسات إنتاج الطاقة (CSP)، قمنا بتنفيذ محاكاة لنموذج محرك ستيرلنغ متصلة بمولد كهربائي يتم التحكم فيه بواسطة وحدة تحكم PID باستخدام برنامج ماتلاب وسيمولنك، حيث يقوم بنمذجة ودراسة الأداء الميكانيكي الحراري لمحرك ستيرلنغ والمولد الكهربائي . يمتد مجال النموذج من الطاقة الشمسية (درجة حرارة ثابتة في هذا النموذج) إلى الطاقة الحرارية والميكانيكية والطاقة الكهربائية الناتجة، مما يساعد في دراسة علاقات النظام من خلال الأنظمة الفرعية. النموذج المستخدم هو نموذج غير خطي، يستخدم لدراسة الظواهر العابرة والديناميكية مع محاكاة عملية تشغيل النظام الكاملة من بدء التشغيل إلى حالة الطاقة الكاملة. تمت مناقشة النموذج التفصيلي ونتائج المحاكاة في هذه الورقة بحيث يمكن القول أنه لا توجد مكونات مفيدة لدراسات نمذجة محرك ستيرلنغ، وقد تم تطوير الدراسات الحالية لأنظمة خاصة وليس للأغراض العامة.

الكلمات المفتاحية: الطبق المركز (CSD)، محرك ستيرلنغ، مولد كهربائي، متحكم.PID

Introduction:

Our model study (Stirling engine) generates output energy according to PDS dimensions and focused solar energy on the SE hot end. The main characteristics of the Stirling engine are: the electrical energy generated capacity, the weight of the SE, its type, and the price. For the PDS systems constructions, two parameters are important, the SE output power, and the dimensions of the SE, because these two parameters will affect in design of the PDS system directly, Figure 1. shows the Concentrated Solar Dish with Stirling engine.

The working gas in SEs (e.g. helium, hydrogen, nitrogen or air) works on a closed regenerative thermodynamic cycle, with compression and expansion cycle at different temperature levels.[1]

High temperatures realized by CSP systems make SE a major option of converting solar power to electric, because of its high effectiveness and no emission working process. The SE system has confirmed success working, realizing the world's record of solar-to grid power conversion effectiveness. In addition, one point should be noted that current studies on the (CSP) system model are limited and dispersed.[2]

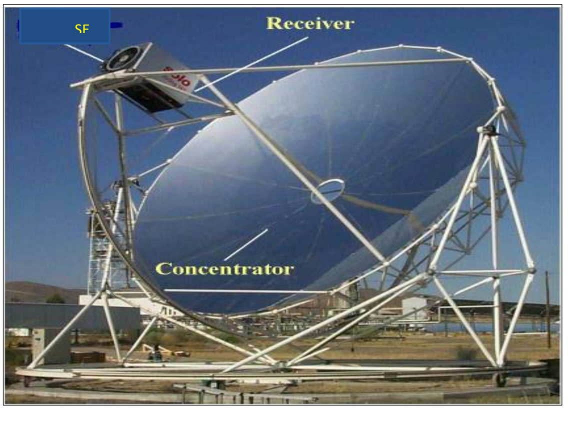


Fig. 1. Concentrated Solar Dish system with Stirling engine [3]

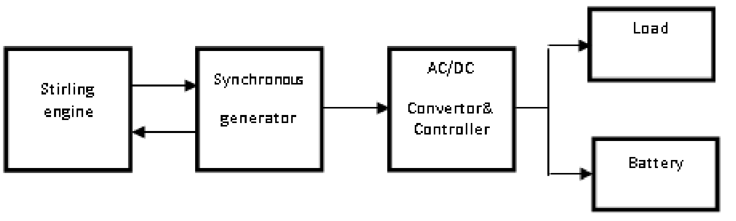


Fig. 2. The studied model block diagram [4]

In this research, concentrated solar Stirling engine is modeled and studied. The solar power is transformed into electric power using the suggested model in two terms: thermal to mechanical stage, and mechanical to electric. The system constructed of three main devices: Stirling engine, electrical generator, and 3-phase controlled rectifier as shown in Figure 2. The concentrated solar energy represented as fixed temperature acting in the model, and Matlab/Simulink are used to model the mechanical and electrical parts of the system [5].

Modeling study:

2.1. Thermomechanical system:

Stirling engine is the major device used to generate a mechanical power (Figure 3.) by the affecting heat. Temperature acting in the hot edge of the SE that is represented the concentrated solar heat, is assumed as a constant temperature (T_h). The model process of the Stirling engine is represented by a set of equations that discussed later. The wasted heat from the cylinder is (S_h), as well as, the low temperature represented as a fixed temperature, (T_c), while it's wasted heat is represented as (S_c).

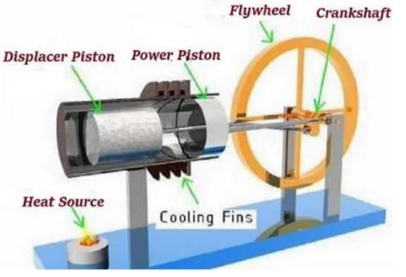


Fig. 3. Schematic diagram of Stirling engine

To represent the cylinder leakage, first port follows the lack of mass out of the cylinder is represented as a fixed pressure source. The second port represents waste variations. The variations are occurred by flow of mass, wasted heat flow, and wasted flux to low temperature side. The last one is related with change of volume. Cylinder pressure affects into the power piston that is represented as a fixed converter. The piston affects into the main shaft linkage, represented as a modulated transformer. Main shaft is represented as inertia, whilst the losses of friction are represented as a resistance with damping coefficient (b). The main suggestions for modeling are [6]:

- Collected friction element (b) to control speed of the engine.
- No wasted power out of the heat piston.
- Low mass pistons.
- Acting temperature is fixed and uniform.
- All engine leakage is out of power cylinder.
- Heat piston has a sinusoidal 90^{o} movement ahead of power piston.

Modeling of SE is performed using MATLAB & Simulink with using a set of differential equations: [6]

$$x = R_e(1 + sin\theta) \tag{1}$$

$$A_h = A_{sc}(1 + cos\theta) \tag{2}$$

$$A_c = A_{sc}(1 + cos\theta) + P_{pc}x \tag{3}$$

$$\dot{S}_h = \frac{A_h\mu(T_h - T_e)}{T_e} \tag{4}$$

$$\dot{S}_c = \frac{A_c\mu(T_e - T_c)}{T_e} \tag{5}$$

$$\dot{N}_e = -A_l\sqrt{2p_c(p_e - p_a)} \tag{6}$$

$$\dot{S}_a = \frac{S_e}{N_e}\dot{N}_a \tag{7}$$

$$\dot{S}_e = \dot{S}_h - \dot{S}_c + \dot{S}_a \tag{8}$$

$$V_e = V_c + A_{px} \tag{9}$$

$$\bar{v}_e = \frac{V_e}{mN_e} \tag{10}$$

$$T_e = T_o\left(\frac{\bar{v}_e}{\bar{v}_o}\right)^{\frac{-R}{C_v}} exp\frac{\bar{S}_e - \bar{S}_o}{C_v} \tag{11}$$

$$P_e = P_o\left(\frac{\bar{v}_e}{\bar{v}_o}\right)^{-\left(\frac{R}{C_v}+1\right)} exp\frac{\bar{S}_e - \bar{S}_o}{C_v} \tag{12}$$

$$F_e = (P_e - P_a)A_p \tag{13}$$

$$\tau_{mech} = F_eR_ecos\theta \tag{14}$$

$$T_{mech} - T_{elec} = b\dot{\theta} + I\ddot{\theta} \tag{15}$$

Where:

θ rotational angle of SE shaft;

$\dot{\theta}$ rotational speed of SE shaft;

$\ddot{\theta}$ rotational acceleration of the SE shaft;

S_e total wasted air of the cylinder;

N_e No. of moles of air in the cylinder;

S_h wasted high temperature to air;

S_c wasted low temperature from air;

R_e linkage shaft radius of SE;

A_{sc} heat transfer of cylinder surface area;

P_{pc} power piston circumference;

A_h high heat transfer area;

A_c heat sink transfer area;
T_e air temperature inside the engine;
A_l leak area;
A_p power piston area;
V_c volume of air in cylinder;
M air molar mass;
R airgas constant;
$\dot{S}_o$ specified waste air at T_c;
T_o initial temperature in the cylinder;
P_a air pressure;
P_o cylinder pressure;
C_v specific heat at constant volume;
T_{mech} mechanical torque;
T_{elec} electric torque;
b damping coefficient;
I main shaft inertia;
μ cylinder's heat transfer coefficient.

Thermo-mechanical relations of Stirling engine are given in Eqs. (1 ~ 13), while Eq. (14) represents mechanical torque. Stirling engine is coupled with electric generator through a same shaft to consider and study the electro-mechanical dynamic relation of Stirling engine. Eq. (15) represented the rotation speed of the main shaft through the acting mechanical torque (T_{mech}) as well as the generator electromagnetic torque (T_{elec}).

2.2. Electrical Generator:

The basic feature of generator is that it doesn't need any exterior excitation current. It produces AC voltage, and for a DC voltage, a bridge rectifier is connected to its output terminals [7, 8]. The generator mainly used to transform mechanical rotation to electric power. For the sinusoidal

model, the flux setup by the permanent magnets in the stator is assumes sinusoidal.
The following differential equations which represented the currents in the (q-d frame) of the generator are used to model the electric generator [9]. It can note that all of parameters are indicated to the stator, and the model is implemented in MATLAB & Simulink environment.

$$\frac{d}{dt}i_d = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}P\omega_r i_q \quad (16)$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}v_d - \frac{R}{L_q}i_q - \frac{L_d}{L_q}P\omega_r i_d - \frac{\lambda P\omega_r}{L_q} \quad (17)$$

$$\tau_{elec} = 1.5P\left[\lambda i_q + \left(L_d - L_q\right)i_d i_q\right] \quad (18)$$

Where:

$i_d i_q$ currents in (q) and (d) axes.
$v_d v_q$ voltages in (q) and (d) axes.
$L_d L_q$ inductances in (q) and (d) axes.
R resistor of stator windings.
ω_r rotational speed.
P No. of pairs.
τ_{elec} electromagnetic torque.
λ flux produced by permanent magnets of rotor in the stator phase.

2.3. Rectifier:

It transforms 3-phase AC voltage to DC which utilized to feed the load and/or charge the battery. Rectifier constructed of: 3-phase full bridge rectifier transforms AC voltages to a DC one, and a controller which controls the rectifier voltage at a required value.
A 3-phase bridge rectifier is normally utilized for various power applications since it is extremely proficient and well known. During numerous implementations, there is no need

for extra filter because the o/p ripple voltages are low. Regardless of the necessity of using filter, parameters of the filter are generally with low values [10].
Converter is utilized to control the O/P DC voltage according to load changing and input voltage varieties. It additionally decreases the ripple components in the output DC under necessary level [8]. Converter consists of a PID controller that controls DC voltage at 110 V as shown in (figure 4.), where the components of the convertor are implemented using Matlab & Simulink.

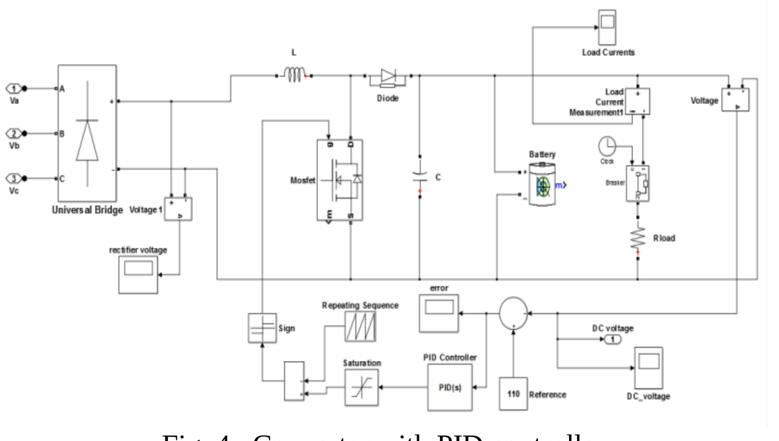


Fig. 4. Converter with PID controller

2.4. Load and Battery

The output DC voltage is used to charge the battery and/or to feed the load. Battery is employed to save the power and to feed the load when no solar energy offers. The Stirling engine with electric generator is generating the electric power, which used to charge the battery, while the battery discharges to supply the load. Primary charge of the battery is 70% at the starting of the simulation, and it rises to 100 percent (full charge) as the generator is working, and reduces to less than

70 percent if there is a lack in solar power, at that time the electric battery used to feed the load.

3. Results

3.1. Simulation results for prepared blocks:

The behavior of the modeled engine is studied in different operating conditions according to various applied temperatures (T_h, T_c) and different load resistances using simulation model as in (figure 5.).

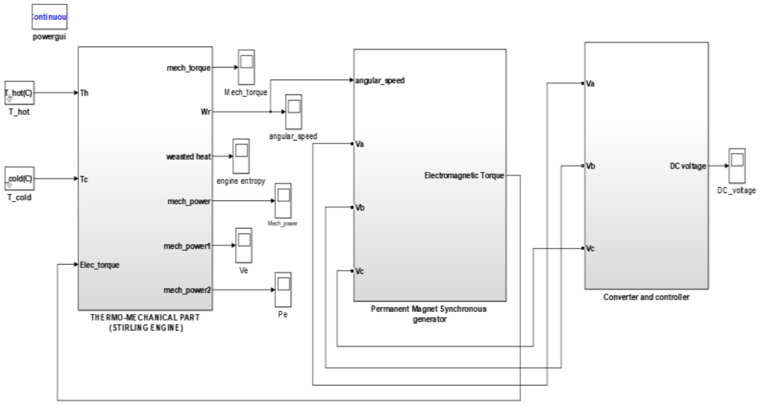


Fig. 5. Simulation model

Mechanical torque and output power of the electric generator according to change of high temperature (T_h) are shown in (figure 6.). From the figure, it can be noted that increasing of (T_h) causes an increase in torque and the output power. There are some oscillations appear on the shaft rotational velocity and electric torque which are regard to physical working of the reciprocating Stirling engine.

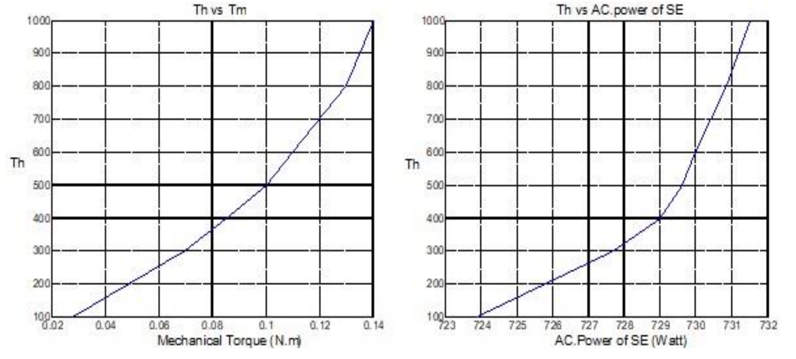


Fig. 6. Applied temperature (Th) Vs mechanical torque and AC power

The vibration in the Stirling engine shaft will appear on the o/p voltage of the generator as a result of connecting the Stirling engine and electric generator on the same pivot. Using of PID controller eliminate any ripple on the O/P DC voltage, where the amplitude of the ripple decreases by increase of the load

The generated voltage and current are shown in figure 7. and figure 8. respectively.

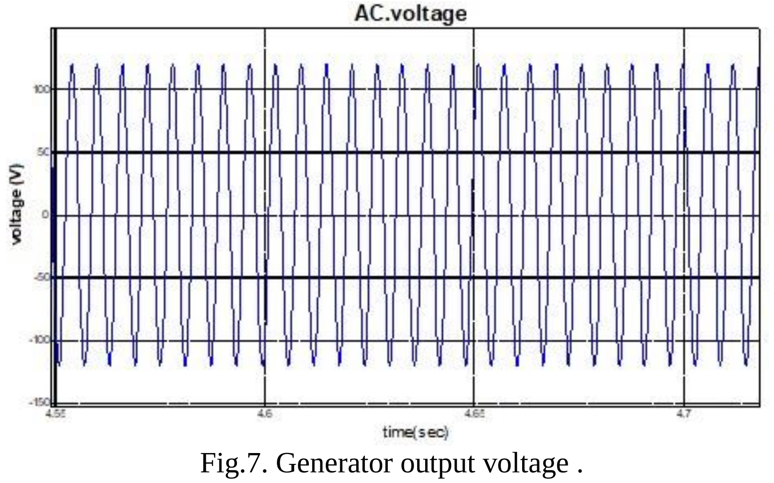


Fig.7. Generator output voltage .

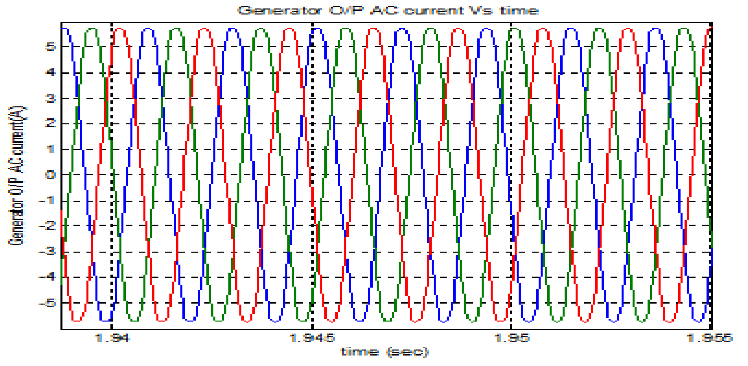


Fig. 8. The output AC current

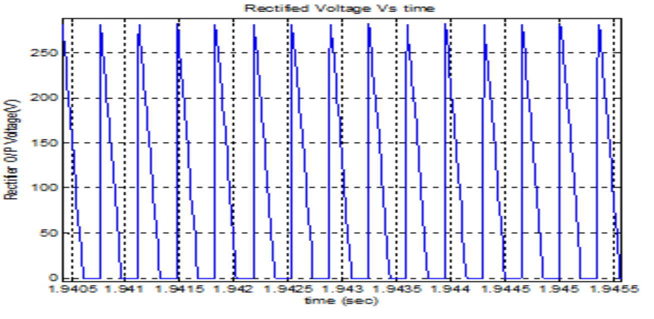


Fig. 9. The rectifier o/p voltage.

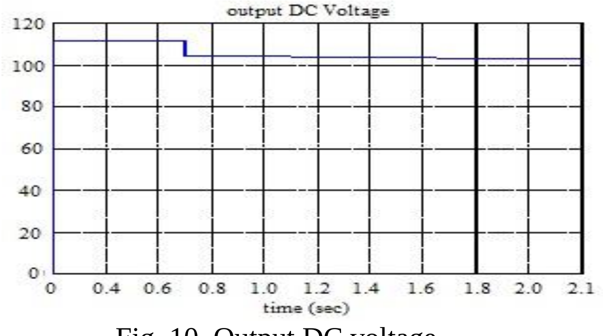


Fig. 10. Output DC voltage.

Rectifier O/P voltage is shown in figure 9. O/P DC voltage is about 110 V as shows in figure 10. Change of DC load causes drop not more of 5% on O/P voltage. Furthermore, the O/P voltage oscillations are eliminated because of the influence of the PID controller.

3.2. Different scenarios

If there is a need to use a Stirling engine in a different operating conditions, there are some parameters may take in consideration to be modified, one is the leakage area that affected directly in rotational velocity, from figure 11., we can note that the motor rotational speed in (rpm) decreases as leakage increases, also from simulation we deduce that the sink heat should be low (air temperature) for a high performance, if (Tc) higher, performance will be low even the difference (Th - Tc) is constant. Another parameter that we evaluated is changing the engine total frictions represents by viscous damping coefficient (b), which also affected in the rotational velocity, and therefore in mechanical power, generator AC voltage,

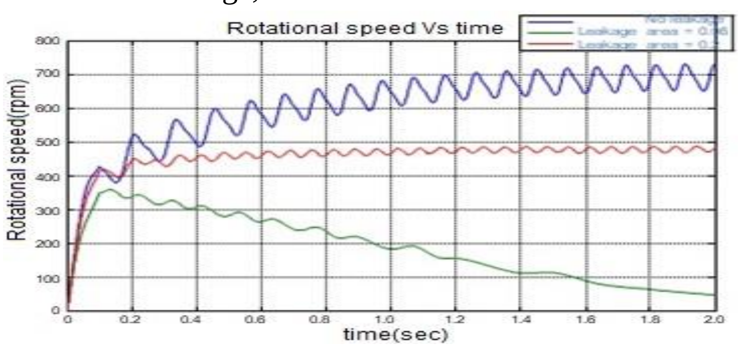
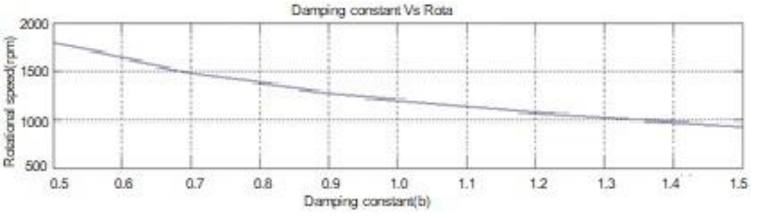
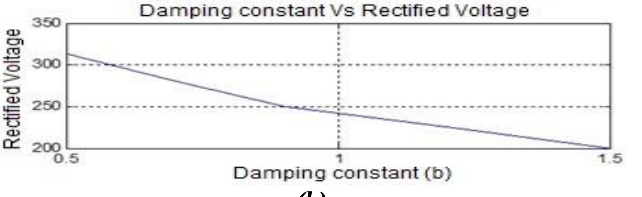


Fig 11: Angular velocity for different leakage areas

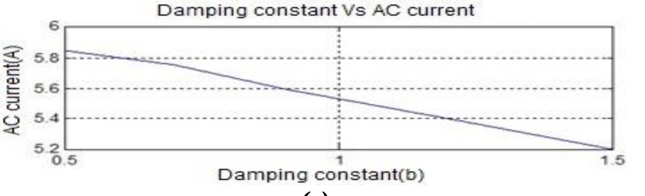
AC current, and rectifier o/p voltage figure 12. In general, using of Stirling engine in different applications needs some modifications in some of the thermal and mechanical parameters depends on the applied heat and the required output power.



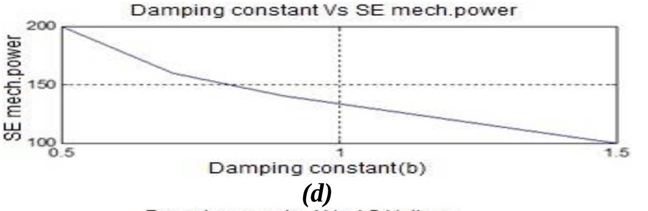
(a)



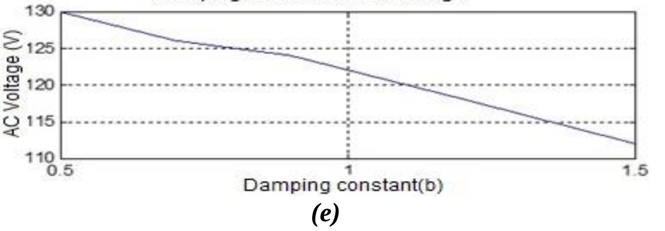
(b)



(c)



(d)



(e)

Fig 12: Affect of engine total friction (damping factor (b)) with: a) angular speed, b)rectifier voltage,
c) AC current, d) mech. Power, e) AC voltage

Conclusion

In this research, the model that constructed of thermal, mechanical, and electrical parts, respectively, was developed using MATLAB & SIMULINK. The result of Simulink emphasize that the represented Simulink model shows a pragmatic impersonation of the system under applied various load. Mechanical and electrical parts connection was represented, and it shows that normal work of the Stirling engine with vibration influence on the angular velocity and mechanical torque, as well as on the angular velocity and electric inertia of the generator. Rectifier transfers AC voltage to DC, and then PID controller works to eliminate the ripple waves on the O/P voltage which feeds to load and charge the battery. The presented system can be applied as DC as well as AC supply source (without converter), or as an off_grid generation system which can feed a load, taking the advantage of the effective Stirling engine and the renewable solar energy as an energy source.

Finally, using of this simulation study and according to the required output power of the modeled system, we can make a manufacturing prototype of the mechanical parts of SE with a proper dimensions and weights, and then construct the PDS system.

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