

Study on A Novel Modeling Method for the Electromagnetic Flywheel Systems

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ABSTRACT— This study proposes a new modeling method for nonlinear systems based on a genetic algorithm (GA). Through this method, the transfer functions of the above unidentified systems can be identified. This method would well help the nonlinear systems to find out their optimal solutions in controls. First, the physical input-output data pairs of the unidentified system should be collected. Next, the coefficients of the first second-order transfer function can be identified by GA. Last, based on the errors between the physical data pair and the first second-order transfer function; similarly the second second-order transfer functions can be identified by GA.

So far as known, electromagnetic flywheel (EF) systems are with many uncertainties, such as nonlinear electromechanical coupling and electromagnetic saturation, etc. They are difficult to accurately modeling by traditional mathematic ways that restrict the control and application of them. In order to confirm the effectiveness and feasibility of this proposed method, an EF system is setup for this study. By assessing the results of calculations and experiments shows that the proposed method is possible to be applied for any nonlinear systems.

INDEX TERMS— nonlinear system, transfer function modeling, genetic algorithm.

I. INTRODUCTION

There are many types of modeling methods which can be divided into linear and nonlinear. The common method of linear modeling is linear regression [1]. This method is simple and is the most widely used mathematical model. But it establishes a more complex nonlinear system model which is not satisfactory in the effect. Neural network [2], adaptive neural fuzzy systems [3] and nonlinear regression [4] are common nonlinear modeling methods. They can model data very accurately by these methods. But these models will be less obvious to the presentation of the mathematical properties which can't derive the mathematical model and to use. It needs to use the Taguchi method or genetic algorithms to be optimized [5, 6]. And the solution may be just a regional solution. Making the step is complicated, so the calculation amount is much larger. Because of this, the application is restricted.

The modeling method is proposed on this study. The first step, the physical input-output data pairs of the unidentified system should be collected. Next, the coefficients of the first

second-order transfer function can be identified by optimization method, such as GA or the least squares method, etc. Last, based on the errors between the physical data pair and the first second-order transfer function; similarly the second second-order transfer functions can be identified by optimization method. The purpose of this step is error compensation. The experimental flow chart is show as Fig.1.

Recently, flywheel energy storage technology is often used in the mechanical rotation system[7,8]. The technology used to store system kinetic energy. To wait until the energy is needed, then released the kinetic energy, or in used to balance the speed instantaneous moment carrying instant variation volatility. Common flywheels divided into two kinds. One kind of the traditional is fixed inertia flywheel. Its structure is relatively simple. The disadvantage will be energy dragging phenomenon on starts. The other is variable inertia flywheel. The advantage is that which not easy cause to produce energy dragging and it is steady to output the energy output on the start of the flywheel. Variable inertia flywheel can change the relationship moment of inertia. Even if the system can also be a relatively stable output in severe deceleration or acceleration [9]. The disadvantage is more difficult to achieve precise control. The variable inertia flywheel's structure is complex, so caused bulky and less prone to maintenance. This study employed electromagnetic flywheel (EF) system which is based on the adjustment of the flywheel speed up to control the kinetic energy from excitation current. The advantages of the EF system are sizes small, easy control and not easy to malfunction, etc, so the EF system is better than the variable inertia flywheel.

Because the EF system has a lot of complex nonlinear uncertainties, such as electromechanical coupling and electromagnetic saturation, etc, there would be a lot of restrictions and difficulties for application and design for the traditional mathematical ways. The EF system is characterized with many uncertain natures, so the system is designed and implemented to confirm the effectiveness of the proposed method in this study. About the details of the EF system design, setup, and experiment processes are introduced as follows section 2.

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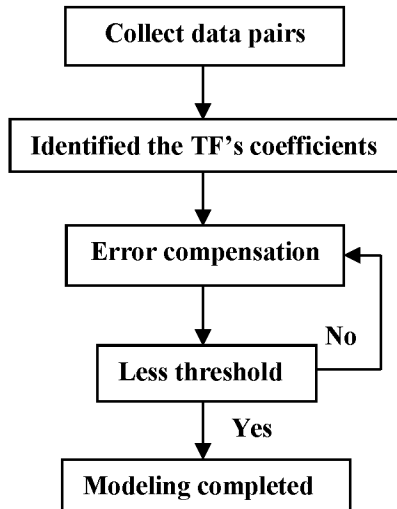


Fig.1 The experimental flow chart

II. THE EXPERIMENT PLATFORM DESIGN AND PARAMETER MEASUREMENT

A. Laboratory equipment.

Electromagnetic flywheel system platform design is show Fig. 2. Sections of components were as follows: ① Motor/generator, ② flywheel(refer with: Fig. 3), ③ Charging and discharging control box, ④ Power analyzer (DM2436AB), ⑤ Motor drive (DELTA 220V/2.2kW), ⑥ Excitation voltage and current control box, ⑦ Hand turn-load control box.

1.Experimental platform(refer with: Fig. 2): The experimental platform by the motor via a coupling passed directly kinetic energy to the flywheel, so the method can reduce the energy loss in the transmission.

2. Charge and discharge control box: It select the mode of charging and discharging by storage and output switch.

3. Power analyzer: It can measure discharge data, such as voltage, current and power factor.

4. Motor drive: It can adjust the frequency of the motor and display the input current frequency of the reference data.

5. Excitation voltage and current control box: This can adjust the output of the excitation current and the voltage.

6. Hand turn-load control box: Hand in the manner to adjust the size of the load resistor in order to achieve the purpose of controlling the output power.

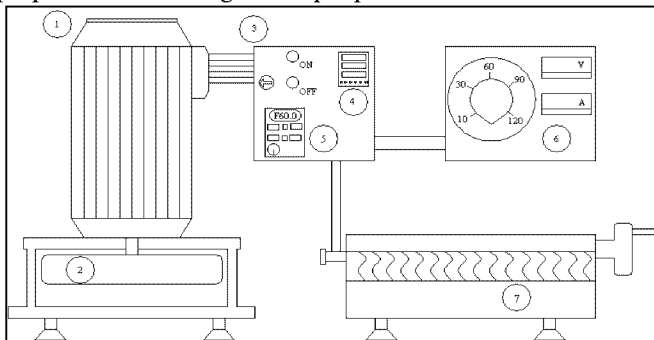


Fig.2 Electromagnetic flywheel system design

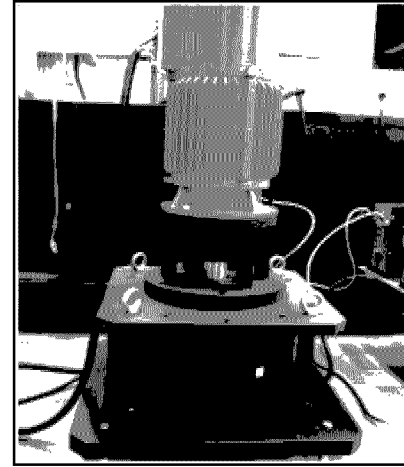


Fig.3 Electromagnetic flywheel system implementation

B. Parameter setting and measurement.

In this study, the experimental approach achieved flywheel charge kinetic energy in relation to time that understand the flywheel of charge characteristics. The experimental divided into nine sections and in accordance with the frequency 20,25,30,35,40,45,50,55 and 60Hz. It is calculated the flywheel output and input of energy from the flywheel speed measurement in the experiment. It Automatically grabed data from computer two seconds per interval sum. The flywheel energy storage system parameters are in Table 1.

Table 1 Flywheel energy storage system parameter

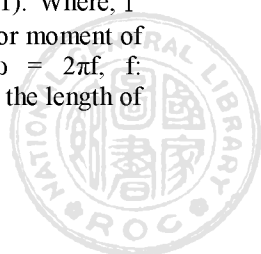
Motor rated voltage	220V
Motor rated current	1.9A
Motor horsepower	2HP
Flywheel weight	60kg
Flywheel Material	Iron
Flywheel radius	0.15m

III. METHODS

A. Flywheel energy storage [10]

A flywheel stores energy in a rotating mass. According to the system inertia and the speed of the kinetic energy of the rotating mass, a given amount to be stored as rotational energy. Kinetic energy is transferred in and out of the flywheel with an electrical machine that can function either as a motor or generator depending on the load angle (phase angle) operation. Converted to a torque as a motor, electrical energy is supplied to the stator windings, applied to the rotor to rotate faster and gain kinetic energy. The kinetic energy of the stored patterns is applied from the generator rotor torque, and will be converted into electrical energy. Flywheel power electronics need to control power output, speed and frequency, etc.

When the flywheel is rotary, the amount of the stored energy $E_c(J)$ can be expressed by the equation(1). Where, I ($kg\cdot m^2$) is the rotational inertia of the flywheel (or moment of inertia); $\omega(rad/s)$ is the angular velocity ($\omega = 2\pi f$, f : revolutions per second, the number of turns); a is the length of



the cylinder; ρ is the density of the cylinder material. The moment of inertia for the measurement of has inertia of the object around a central axis. When the quality of the solid disc-type is $M(\text{kg})$ and the radius is $R(\text{m})$, moment of inertia I is as follows equation (2). The other dominating shape is allow circular cylinder, approximating a composite or steel rim attached to a shaft with a web, which is equation(3). The equation(2) is substitute into equation(1). The flywheel energy storage can be obtained as in (4).

$$E_c = \frac{1}{2} I \omega^2 = \frac{1}{2} R^4 \pi a \rho \quad (1)$$

$$I = \frac{1}{2} M R^2 \quad (2)$$

$$I = \frac{1}{4} M (R_0^2 + R_1^2) = \frac{1}{4} \pi a \rho (R_0^2 + R_1^2) \quad (3)$$

$$E_c = \frac{1}{4} M R^2 \omega^2 \quad (4)$$



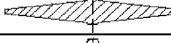

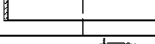

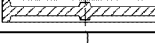
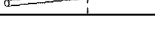
Eq. (1) shows that the most efficient way to increase the stored energy is to speed up the flywheel. The speed limit shall be such that the flywheel below the inertial load stress range σ tensile stress intensity. Lighter materials to develop a lower inertial load, at a given speed, so the composite material, having a low density and a high tensile strength, are excellent for storing kinetic energy. The maximum energy density with respect to volume and mass, respectively, are (5) and (6).

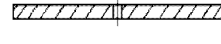
Where e_v and e_m are kinetic energy per unit volume or mass, respectively, K is the shape factor, σ is the maximum stress of the flywheel energy storage system. ρ is the mass density of the flywheel energy storage system. If the height of the disk is small compared with the diameter, and homogenous isotropic materials with Poisson ratio of 0.3, i.e. steel, are used, the K factors are given in Table.2 [11].

$$e_v = K \sigma \quad (5)$$

$$e_m = K \frac{\sigma}{\rho} \quad (6)$$

Table 2 Shape-factor K for different planar stress geometries

Flywheel geometry	Cross section	Shape factor K
Disc		1.000
Modified constant stress disc		0.931
Conical disc		0.806
Flat unpierced disc		0.606
Thin firm		0.500
Shaped bar		0.500
Rim with web		0.400
Single bar		0.333

Flat pierced bar		0.305
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B. System modeling method.

The research method is based on the transfer function to approximate the experimental data. And the transfer function of the inverse Laplace transform obtains a maximum time t and the maximum power point y after differential (refer with: Eq. 7-Eq. 9).

$$\mathcal{L}^{-1}\{tf_1\} = y(t) \quad (7)$$

$$y' = \frac{dy}{dt} = 0, \quad t = t_{\max} \quad (8)$$

$$y = y(t_{\max}) \quad (9)$$

And a second-order transfer function with three unknowns X_1, X_2, X_3 is as follows equation (10). The first step is the inverse Laplace transform to the transfer function(refer with: Eq. 7). The objective function is set to reduce the output value y minus the target output value d that is E (refer with: Eq. 11). The time points t and the target values brought into the equation (11) which is equation (12).

$$tf_1 = \frac{X_3}{X_2 s^2 + X_1 s + 1} \quad (10)$$

$$E = y(t) - d \quad (11)$$

$$E = y(t_1) - d_1 + \dots + y(t_n) - d_n \quad (12)$$

The equation is complicated so the common method will cause difficult to calculate. GA has a diversity problem-solving skill that applied to complex nonlinear mathematical problem and can quick to obtain a fine solution. So this method have been applied to a wide range of problems [12]. Therefore, GA obtains three unknowns X_1, X_2, X_3 solutions in this study. If GA is the inappropriate choice of gene operator operating, the part of offspring range is smaller in the activities. So it always focused on genes parental values in the vicinity. Therefore, it is difficult to escape the regional solution [13]. The method [14] obtains the reference value of the unknown boundary value in this study.

C. Approximates damped response of the model obtaining [14]

The response approximates that an underdamped second-order system with some element of dead time, as in Eq. 13.

$$G_3(S) = \frac{C_\infty}{\tau^2 S^2 + 2\zeta\tau S + 1} e^{-ds} \quad (13)$$

It is assumed that the open-loop system is underdamped. And a unit step signal input of the controlled body. The step response is as Fig. 4.

Where H is overshoot, d is dead time, ζ is damping ratio and C_∞ is settling value.



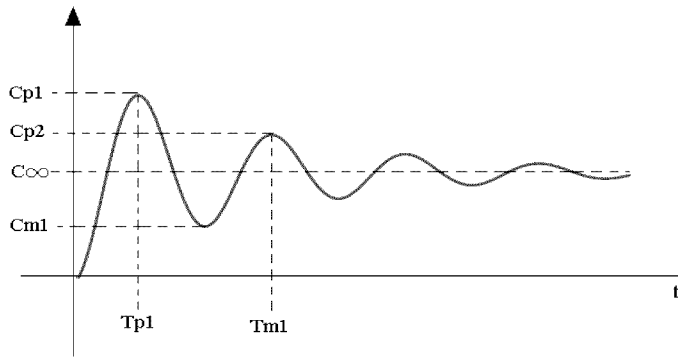


Fig.4The step response

$$\zeta = \frac{-\ln(H)}{\sqrt{\pi^2 + \ln^2(H)}} \quad (14)$$

$$\tau = \frac{(T_{m1} - T_{p1})\sqrt{1 - \zeta^2}}{\pi} \quad (15)$$

$$d = 2T_{p1} - T_{m1} \quad (16)$$

$$C_{\infty} = \frac{C_{p1}C_{p2} - C_{m1}^2}{C_{p1} + C_{p2} - 2C_{m1}} \quad (17)$$

$$H = \frac{1}{3} \left[\frac{C_{p1} - C_{\infty}}{C_{\infty}} + \frac{C_{\infty} - C_{m1}}{C_{p1} - C_{\infty}} + \frac{C_{p2} - C_{\infty}}{C_{\infty} - C_{m1}} \right] \quad (18)$$

These equations (eq.14-eq18) and the step response have relative.

D. The operation of Genetic Algorithm[15]

The operation of Genetic Algorithm is divided into four steps on Fitness computation, Selection, Crossover and Mutation, shown as fig. 5.

Fitness computation can be seen as an interface between Genetic Algorithm and the optimization problem, which depends on the actual problem completely.

Selection operation also can be implemented by random method. First step, the random number between 0 and 1 with uniform distribution is produced. Second, if any string's selection probability is 40%, the string will be selected when the random number is between 0 and 0.4, otherwise the string must be eliminated.

Crossover operation can be divided into following two steps. The first step is to match each two members by random which has selected and produced newly in the match pool. The second step is to make them crossover and breed.

Mutation operation is to change the value of a string's position randomly at a very small probability. It will change the string bit that is randomly selected from 1 to 0 or from 0 to 1 for the binary string. Mutation probability is usually very small, only someone in thousands. As shown figure 1, such a step of Genetic Algorithm operation is processed one time; the problem's solution will be very close to the optimal solution.

Therefore, as long as the process goes on, the optimal solution will be gotten finally. Because each step operation is very simple and the dependence on the actual problem is very small, this algorithm is very prevailing use on solving the optimization problems.

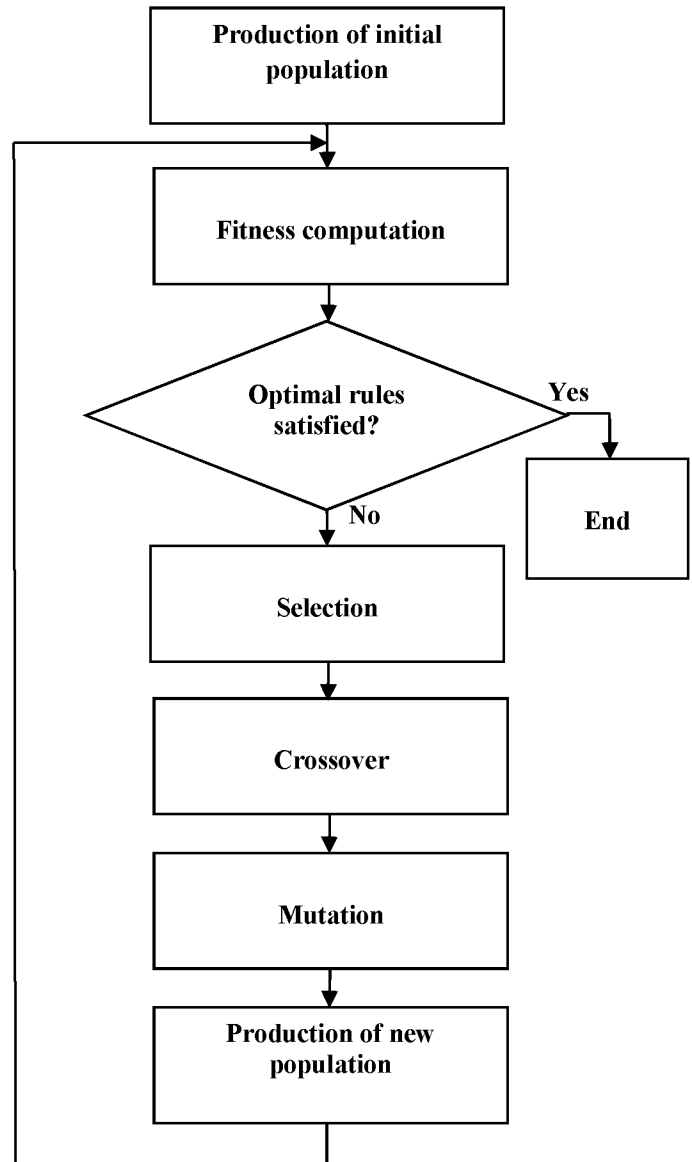
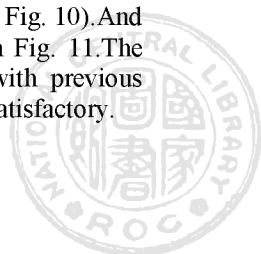


Fig.5 The operation of Genetic Algorithm

E. Error compensation.

The case study research is charging curve at 1765rpm. The transfer function tf_1 (refer with: Eq. 19) approximation of this curve with the research method. Approximation result is shown in Fig. 6. The root mean square error (RMSE) is 1.07 in the performance of the study. The discharge curve is a very complex non-linear curve. If using one transfer function approximate it, the error is too large. This research proposes the transfer function to do error compensation. Fig. 7 is an example of the error curve. A transfer function tf_2 (refer with: Eq. 20) approximate error curve (refer with: Fig. 8). tf_1 plus tf_2 approximate result is shown in Fig. 9. There are large errors between 50 to 90 seconds. The transfer function tf_3 (refer with: Eq. 21) approximate error curve (refer with: Fig. 10). And tf_1 plus tf_2 and tf_3 approximate result is shown in Fig. 11. The RMSE reduced to 0.12. The result compared with previous result. It means the compensation effect is quite satisfactory.



$$tf_1 = \frac{11.371}{1439.996s^2 + 0.004s + 1} \quad (19)$$

$$tf_2 = \frac{-0.828}{198.196s^2 + 0.001s + 1} \quad (20)$$

$$tf_3 = \frac{1}{38.652s^2 + 2.179s + 1} e^{-66s} \quad (21)$$

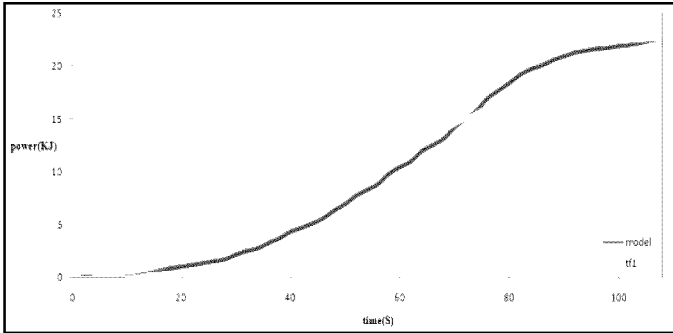


Fig.6 tf_1 approximation result

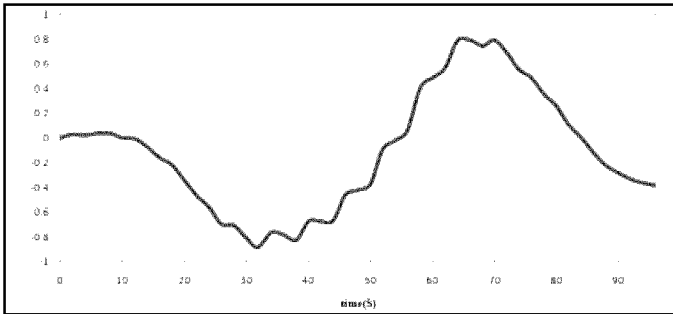


Fig.7 Error curve

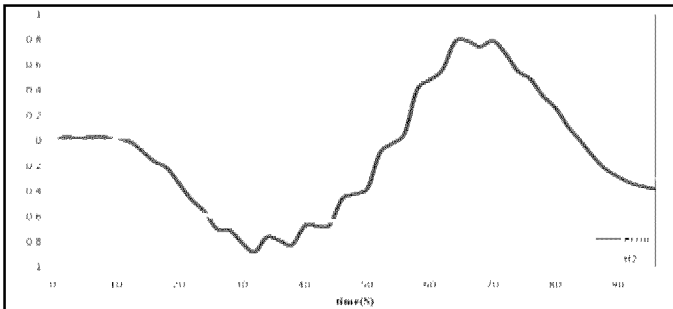


Fig.8 tf_2 approximate error curve



Fig.9 tf_1 and tf_2 approximation result

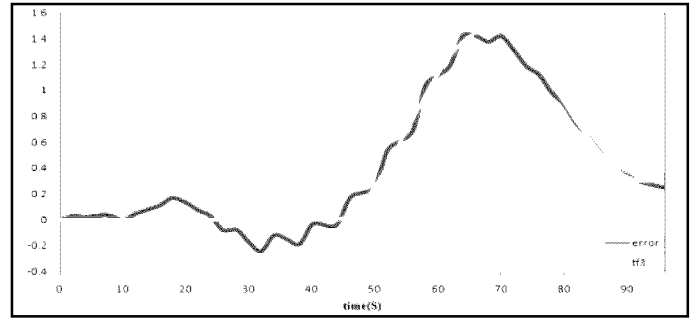


Fig.10 tf_3 approximate error curve

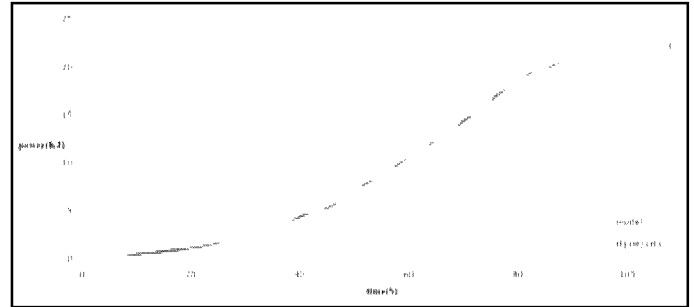


Fig.11 tf_1 , tf_2 and tf_3 approximation result

IV. MODEL OF FLYWHEEL ENERGY STORAGE SYSTEM

A. Calculated flywheel charging kinetic energy

For example, when the flywheel speed in 575rpm, the charging and discharging energy (KJ) can be obtain as in Eq.1-Eq4. The charging kinetic curve and discharging kinetic curve are shown Fig. 12 and Fig. 13 in 0-60 seconds.

B. Model of flywheel charging at 1469 rpm

The modeling result is show the Fig 14. RMSE is 0.05. The model substituted into the formul (10) and (11). The output time of the maximum kinetic energy is 51.93 seconds. The maximum charge kinetic energy is 15.06KJ. The experimental result is 15.36KJ.

C. Transfer function model of flywheel energy storage system of the charging kinetic energy.

It is transfer function model of the flywheel charge kinetic energy (refer with: Eq. 22).The speed of each order transfer function models parameters summarized are in Table3. The 1469rpm model's RMSE meet standards when the second transfer function for error compensation.

$$tf = \frac{X_3}{X_2s^2 + X_1s + 1} + \frac{X_6}{X_5s^2 + X_4s + 1} e^{-X_7s} + \frac{X_{10}}{X_9s^2 + X_8s + 1} e^{-X_{11}s} \quad (22)$$



Table 3 The speed of each order transfer function model parameters

	x1	x2	x3	x4	x5	x6
574rpm	1.469	241	1.469	0.001	109.63	-0.27
722rpm	3.62	423.153	2.07	0.066	56.311	-0.188
874rpm	5.391	538.583	3.107	0.001	79.282	-0.392
1015rpm	1.492	602.025	3.913	0.739	23.619	-0.258
1166rpm	0.347	879.618	4.808	0.987	103.218	-0.665
1315rpm	0.084	1008.62	6.426	7.075	19.894	-0.632
1469rpm	0.03	1004.562	7.614	0.002	177.253	-1.11
1614rpm	0.052	1124.122	9.251	1.462	157.348	-1.297
1765rpm	0.004	1439.996	11.371	0.001	198.196	-0.828
	x7	x8	x9	x10	x11	
574rpm	-12					
722rpm		1.609	82.811	0.28	-48	
874rpm	-4	1.788	115.162	0.862	-62	
1015rpm	-14	1.999	27.64	0.492	-36	
1166rpm	-8	1.995	92.846	0.83	-78	
1315rpm	-10	0.002	0.11	0.819	-44	
1469rpm		15.365	8.835	1.057	-84	
1614rpm	-4	3.918	3.362	0.84	-64	
1765rpm		2.179	38.652	1	-66	

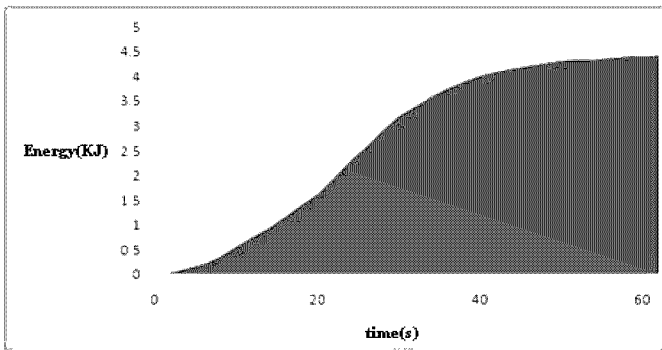


Fig. 12 charging curve at 574rpm

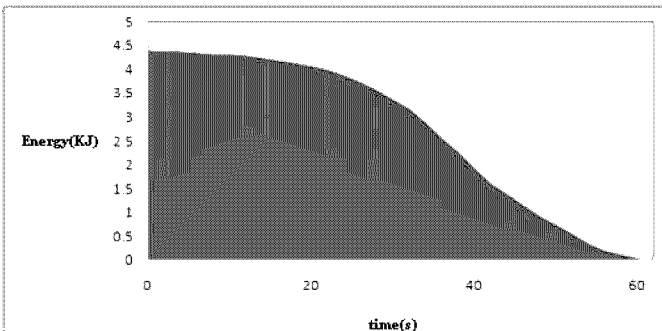


Fig. 13 discharging curve at 574rpm

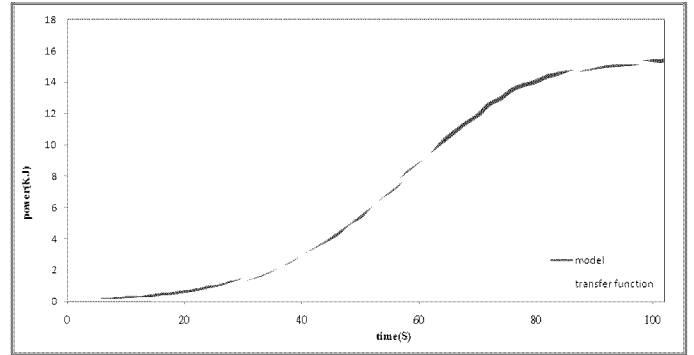


Fig. 14 Modeling result isflywheel energy storage system at 1469rpm

V. CONCLUSIONS

This study proposes a new modeling method for nonlinear systems based on a genetic algorithm (GA). This method can be obtained mathematical model and has very nonlinear characteristics, so the method is better than linear and nonlinear modeling method.

Table 4 RMSE for modeling at 574-1765 rpm

ω (rpm)	RMSE (KJ)
574	0.05
722	0.06
874	0.09
1015	0.13
1166	0.23
1315	0.08
1469	0.19
1614	0.13
1765	0.12

The EF system is designed and implemented for this study. The EF system is in this study to confirm the effectiveness of the proposed method. It is helpful to obtain the optimal solution. This model can provide to the relevant electromagnetic flywheel research as reference. The tests are done at the speed from 574 to 1765rpm. RMSE of each stage charging model is in Table 4. The largest RMSE is 0.23. The smallest RMSE is 0.05 .RMSE of average is 0.12.



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BIOGRAPHIES

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