A Self-Adapted PID System Based on Intrinsic Evolvable Hardware

Wei Zhang and Yuanxiang Li

***Abstract*—Based on intrinsic analog evolvable hardware (EHW) technology, a self-adapted control strategy for hydro-turbine governing system (HGS) is proposed to improve the overall performance and adjust adaptively the parameters as the operating conditions change. Considering the complex dynamic characteristic and uncertainty of HGS, the controller implemented is evolved on ANEHP-Alpha, an analog intrinsic EHW platform based on AN231E04 field programmable analog array (FPAA) device, which is one of the latest models of the dpAsp series based on switched capacitor technology from Anadigm Corporation. A fast pre-evaluation and bad individual elimination method was employed which highly increased the speed of evolution and ensured the devices against damage induced by illegal individuals. Hereboy algorithm (HBA) is employed as the main evolutionary mechanism of this system. In the experiments, comparing with the conventional PID, the evolved controller performs well on inhibiting the effects caused by the external disturbance with higher self-adjusting speed, smaller overshoot and lower sensitivity to the parameters, which indicates that this strategy can effectively improve the robustness, stability and dynamic performance of the hydro-turbine governing systems.**

***Index Terms*—Evolvable hardware, Evolutionary algorithm, FPAA, Pre-evaluation**

I. INTRODUCTION

With the fast development of modern technology, the industrial turbine is widely used as the primary mover in many fields such as hydroelectric power stations. Hydro-turbine governing systems (HGS) are usually used to control the turbine speed [1]. In order to improve the electric quality and ensure the operation stability and reliability of hydro power systems, it is very important to develop reliable HGS controllers.

HGS is a complex automatic control system. Variable work condition of the assembling unit always leads to the alteration of its operational parameters and characteristic. On the other hand, the dynamic process of HGS has to be divided into two different types: small undulation and big undulation. When load or power disturbance is not bigger than ± 10 % rated value or frequency disturbance is less than $\pm 1\%$ rated value, it is called small undulation and the system can be regarded as linear system. Otherwise, it is big undulation, and then the nonlinear characteristic of turbine and the range limitation of governor should not be ignored.

Conventional linear control methods are based on certain, linear model and researches have shown that they were unable to perform optimally over the full range of operating conditions and disturbance [2], [3]. In recent years, there has been considerable interest in application of advanced control such as robust control and adaptive control to HGS [4], [5]. In this paper, based on our previous research, we will propose a new method to design a self-adapted controller based on intrinsic analog evolvable hardware technology.

In 1992, Hugo de Garis put forward the concept of evolvable hardware (EHW) [6]. A typical EHW system is composed of two main components: reconfigurable hardware [7] and reconfiguration mechanism [8]. So, analog EHW can be defined as hardware that is built on software-reconfigurable analogue circuits.

As reconfiguration mechanism, the type of algorithm is usually decided according to the requirements and characteristic of actual systems. Hereboy algorithm (HBA) is an evolution algorithm combined with genetic algorithm and simulated annealing and it can offer better convergence speed than classical simple genetic algorithm (SGA), which is very important for online evolution. Analog reconfigurable hardware is the physical basis of analog EHW technology and basically, the research in this area goes into two directions. One is the specialized analog integrated circuit with only limited programming capabilities. Leading manufacturer in this field is Lattice Semiconductors, makers of the inexpensive but relatively high-performance ispPAC family of analog devices. The other one is the general purpose field programmable analog array (FPAA) [9] and the dpAsp series designed with switched-capacitor technology from Anadigm Inc.® is the most typical production of this type.

In this paper, we will evolve a self-adapted HGS control system on ANEHP-Alpha, an analog intrinsic EHW platform based on AN231E04 FPAA device, which is one of the latest productions of Anadigm's dpAsp series. This controller will be applied to improve the overall performance of the system and adjust adaptively the parameters as the operating conditions change. This paper is organized as follows. Section 2 introduces AN231E04 FPAA device. Section 3 describes the Hereboy algorithm and the fitness function design. Section 4 gives the hydro-turbine governing system model. Section 5 demonstrates the whole system based on ANEHP-Alpha platform and gives the results of experiments. Section 6 draws some conclusions.

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II. Reconfigurable Device

According to the difference of implementation and evaluation strategy, EHW can be divided into three categories: extrinsic EHW (off-line evolution) [10], intrinsic EHW (On-line evolution) and embedded EHW (On-chip evolution). Intrinsic EHW is based on practical circuit implementation and hardware evaluation, which can be performed at high speed. The process of intrinsic evolution is accomplished on the separated algorithm unit (usually a central computer) so that it can be easily controlled and cooperate with other related applications [11]. Intrinsic EHW is a good choice for large-scale self-adaptive real time systems. In this work, the HGS controller is evolved with intrinsic method on a brand new reconfigurable analog device AN231E04.

By the end of the last decade a new type of analog circuit, based on configurable blocks, was introduced to the market: the field programmable analog arrays. Among all kinds of FPAAs, the dpAsp series of Anadigm Inc. ® is the most typical production designed with switched-capacitor technology. To develop intrinsic EHW in a dpAsp device, we employ the AN231K04-DVLP3 development board, which is the latest development kit of Anadigm. The layout of AN231K04 is shown in Fig.1, which can be divided into three parts: 1) DpAsp chip, the most important component of the board. Circuits are configured by the program inside this chip and then the analog signal is processed here. 2) Digital interface, which is connected to PC through a RS232 cable to download the configuration data to the chip and to control the course of signal processing. 3) Analog I/O interface.

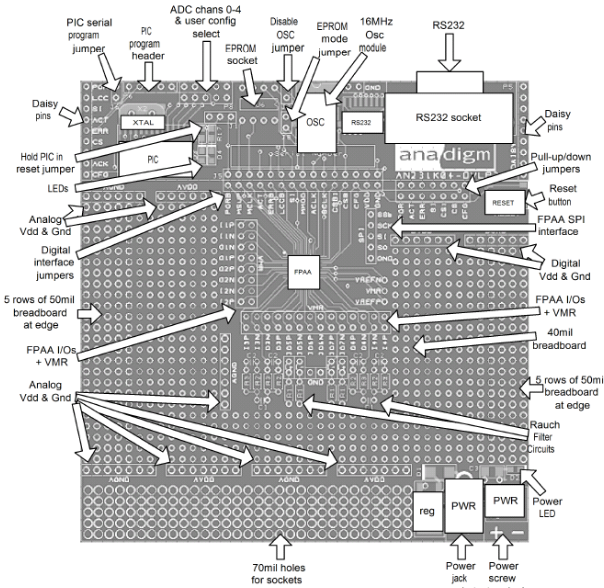

Fig.1 The layout of AN231K04-DVLP3 development board.

The dpAsp device on this development platform is an AN231E04, which is in the third generation of Anadigm FPAA series. It has a lot of advantages to its older counterparts and among them the flexible dynamic reconfiguration ability is most important for EHW. Old devices can be configured any number of times, but an intervening reset is required between each configuration load, so it is hard to develop any EHW application with these devices. AN231E04 is more flexible, allowing for 'on-the-fly' reconfiguration [12] - that means we can reconfigure the device freely without reset. Furthermore, any configuration data can be downloaded in less than 15 ms which ensured the possibility to develop larger-scale complex circuit.

The architecture of AN231E04 is shown in Fig.2. AN231E04 contains a 2x2 matrix of configurable analog blocks (CABs) which in turn can hold a number of predefined analogue functions provided as configurable analog modules (CAMs). I/O capabilities are provided through two dedicated analogue Type1 I/O cells and two analog Type1A I/O cells as input or output. All this I/O cells can be programmed to satisfy the requirement of different I/O type. A Look up Table (LUT) is provided to build special CAMs.

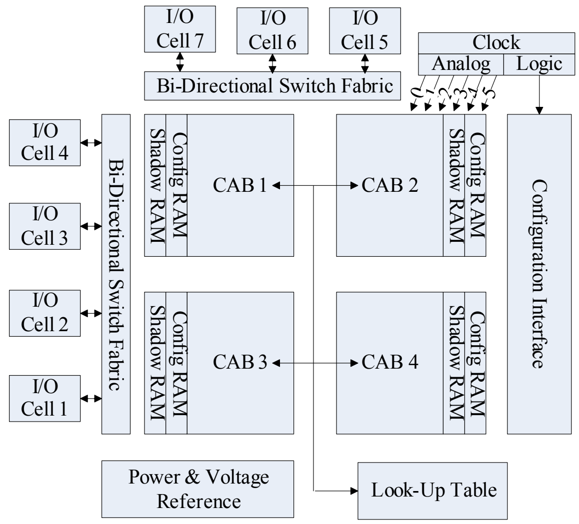

Fig.2 The architecture of AN231E04 dpAsp chip.

This device is based on switched capacitor technology. Switched capacitor circuits [13] are realized with the use of some basic building blocks, such as opAmps, capacitors, switches and non-overlapping clocks. The operation of these circuits is based on the principle of the resistor equivalence of a switched capacitor [13]. This principle is illustrated in Fig.3, where φ_1 and φ_2 are the non-overlapping clocks. In Fig.3–(a), the average current is given by:

$$I_{avg} = C_1(V_1 - V_2)/T . \qquad (1)$$

In (1), T is the clock period. Fig.3–(a) is equivalent to the resistor *Req*, shown in Fig.3–(b). With this technology, integrators, filters, and oscillators can be implemented.

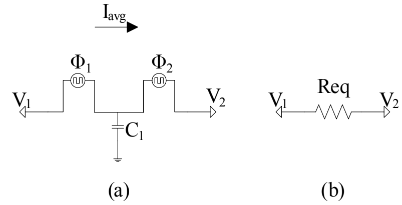

Fig.3 Switched capacitor/resistor equivalence principle.

III. HEREBOY ALGORITHM AND FITNESS FUNCTION

A. Hereboy Algorithm

Hereboy algorithm is an evolution algorithm combined with genetic algorithm and simulated annealing. In the algorithm, several genes are selected randomly to perform mutation operator at a certain probability to search for the best chromosome. More details about HBA can be found in [14].

Many aspects should be considered in the algorithm, such as mutation probability (P_m) and fitness function used to evaluate evolved results. The validity of the search space and speed of searching are related with P_m. If it is too large, searching will become randomly. And if P_m is too small, searching process will get too slow and the probability of convergence will reduce. According to experiences [14], P_m is in the domain of [0.06, 0.2].

B. Fitness Function

The reciprocal of square error per data is usually taken as fitness function. Take two cycles of sine wave as an example, target gain, defined as A_{m0}, is 5, frequency is 1 kHz, and the max voltage value, v_0, is 0.01 volts. The input signal $U_i(t)$ and target output $U_o'(t)$ are expressed as in (2).

$$\begin{aligned} U_i(t) &= 0.01x\sin(2000\pi t) \\ U_o^{'}(t) &= 0.05x\sin(2000\pi t) \end{aligned} \tag{2}$$

Fitness function is presented in (3):

$$Fitness = 1/\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}[U_o(i)-U_o^{'}(i)]^2} \tag{3}$$

$U_o(i)$ and $U_o'(i)$ are one couple of the sampled real and target output voltage value, and n is the number of sampled data. 100 points are sampled in each cycle, so n=201.

The fitness function gets larger while the square error becomes smaller, which means output gets closer to the target value. But not every point of the output signal evolved well, especially in some specific points, such as the peak-to-peak value of a sine wave. It is necessary to adjust the fitness function to satisfy the evolution demand of some special points.

A constraint is taken into account in fitness function in this paper. The reciprocal of the square error is taken as fitness at the beginning of evolution. Then P_a and P_b are taken as the weights of the main fitness function and the additional fitness function separately. Sq_0 is a predetermined square error threshold, and sq is the square error of present evolution. The value of P_a and P_b is determined in (4) as follows.

$$\begin{aligned} P_a &= \begin{cases} 1, sq > sq_0 \\ 0.95, sq \le sq_0 \end{cases} \\ P_b &= \begin{cases} 0, sq > sq_0 \\ 0.05, sq \le sq_0 \end{cases} \end{aligned} \tag{4}$$

Fitness function is depicted as in (5).

$$Fitness = \frac{P_a}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}[U_o(i)-U_o^{'}(i)]^2}} + \frac{P_b}{A_m - A_{m0}} \tag{5}$$

In (5), only square error is calculated in the former stage of the evolution, and the gain joins evaluation only if the square error is no larger than sq_0.

IV. HYDRO-TURBINE GOVERNING SYSTEM MODELS

The HGS includes conduit system, turbine, governor, electro-hydraulic servo system and generator etc. A classical hydro-turbine model for power system is derived with no elastic water hammer effect considered and the corresponding block diagram is shown in Fig.4.

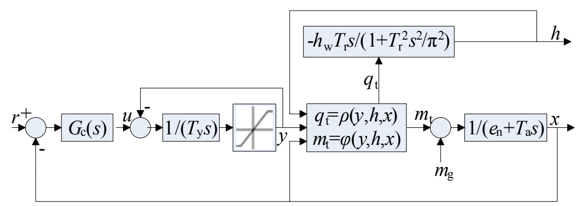

Fig.4 Hydro-turbine governing system scheme.

We take the Francis turbine as an example of turbine model. The nonlinear characteristic of it and the turbine of fixed blade propeller type can be expressed by two equations as (6).

$$\begin{cases} M_t = M_t(H, n, \alpha) \\ Q_t = Q_t(H, n, \alpha) \end{cases} \tag{6}$$

In (6), α is guide vane opening, n is the speed of rotation, Q_t is flow rate, M_t is turbine moment, and H is hydro-turbine water head. When the parameters of turbine vary in the small range at a stable operating point, the above two equations can be linearized as:

$$\begin{cases} m_t = \varphi(y,h,x) = e_x x + e_y y + e_h h \\ q_t = \rho(y,h,x) = e_{qx} x + e_{qy} y + e_{qh} h \end{cases}. \tag{7}$$

In (7), m_t is the torque deviation of turbine, q_t is the flow deviation of turbine, y is gate opening deviation, x is hydro-turbine speed deviation, and h is the hydro-turbine water head deviation. $e_x = \frac{\partial m_t}{\partial x}$ is partial derivative of the torque to speed of turbine. $e_y = \frac{\partial m_t}{\partial y}$ is partial derivative of the torque to gate opening. $e_h = \frac{\partial m_t}{\partial h}$ is partial derivate of the torque to the water head of turbine. $e_{qx} = \frac{\partial q}{\partial x}$ is partial derivative of the flow to speed of turbine. $e_{qy} = \frac{\partial q}{\partial y}$ is partial derivative of the flow to gate opening. $e_{qh}=\frac{\partial q}{\partial y}$ is partial derivative of the flow to the water head of turbine. The plant time-vary parameters result in the transmission coefficients of turbine (e_x, e_y, e_h, e_{qx}, e_{qy}, e_{qh}) variety with the operating situation [15].

The conduit system may be modeled as:

$$h=-T_w\frac{dq_t}{dt}. \tag{8}$$

T_w is water inertia time constant, given as:

$$T_w=LQ_r/(gFH_r). \tag{9}$$

In (9), L and F are the length and cross-sectional area of the conduit; H_r and Q_r are the per-unit base values of the water column head and that of the water flow rate, respectively. g is the gravitational acceleration. The water inertia increases with T_w increasing, and $\frac{dq_t}{dt}$ is derivative of flow to time.

The mathematical model of generator and load is given as:

$$(T_a+T_b)\frac{dx}{dt}+e_g x=m_t-m_{g0} \tag{10}$$

where T_a is unit inertia time constant, T_b is load inertia time constant, m_t is turbine torque, m_{g0} is load torque at rate frequency and $e_g = dm_g / dx$ is derivative of load torque to speed.

The servo system model may be given as:

$$T_y\frac{dy}{dt}+y=u \tag{11}$$

where T_Y is servo system time constant.

This system can be represented by transfer function (12).

$$G(s)=\frac{1}{T_yS+1}\frac{e_y-(e_{qy}e_h-e_{qh}e_y)T_wS}{1+e_{qh}T_WS}\frac{1}{T_aS+e_n} \tag{12}$$

Obviously it has the right half s plane zero. We use the output redefinition technique to deal with the right half s plane zero [16]. Let $x_1=x$, $x_2=-e_nx+m_t$, and $x_3=-(e_n^2x+e_nm_t)/T_a+[T_ye_y-(e_{qh}e_h-e_{qh}e_y)T_wy]/T_yT_we_{qh}$. Then the state space equitation is obtained after redefining the state variable and output:

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=x_3\\ \dot{x}_3=f(x)+u(x)\\ y=[e_yx_1-(e_{qy}e_h-e_{qh}e_y)T_Wx_2]/(T_aT_yT_we_{qh})\end{cases} \tag{13}$$

and in (13),

$$f(x)=\frac{e_n}{T_aT_yT_we_{qh}}x_1+\frac{T_a+T_ye_n+T_We_{qh}e_n}{T_aT_yT_we_{qh}}x_2+\frac{T_aT_y+T_aT_We_{qh}+T_aT_yT_We_{qh}}{T_aT_yT_we_{qh}}x_3. \tag{14}$$

After state and output redefinition the HGS can be controlled as nonlinear SISO system.

V. Evolution Platform and Results of Experiments

The work of this paper is a part of analog EHW research section in No.2007AA01Z290 Project of Chinese National High-Tech Research and Development Program (863 Program). As the experimental basis of this project, ANEHP-Alpha, a high-speed intrinsic EHW platform for large-scale analog circuit based on AN231E04 had been defined. In this paper, an on-line evolvable HGS controller will be designed on ANEHP-Alpha.

A. ANEHP-Alpha Platform

The structure of ANEHP-Alpha is shown in Fig.5 (including HGS system). The whole EHW platform is composed of three main parts and several assistant modules.

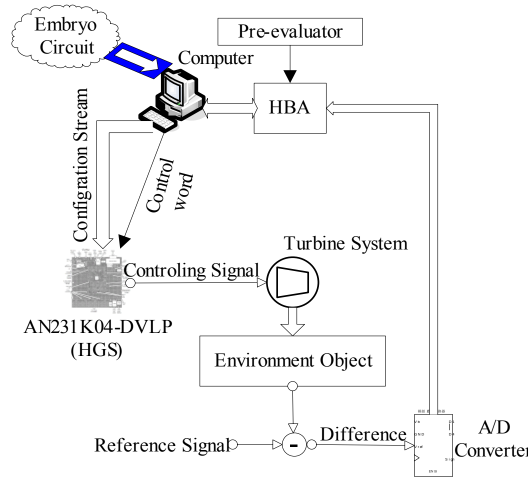

Fig.5 HGS controller based on ANEHP-Alpha platform

Computer. Computer is employed to generate the initial embryo circuit and execute the evolution algorithm. Anadigm has offered powerful EDA tool Anadigm Designer 2 for its dpAsps with the ability to create embryo circuit, simulate with embedded signal generator and create c++ code prototype for dynamic configuration.

AN231K04. AN231K04-DVLP3 development board can actually run each individual circuit during the course of evolution. In practice, not all individuals are downloaded to development board out of consideration for evolution speed.

A/D Converter. The external A/D circuit transforms the analog output of AN231K04-DVLP3 development board into digital signal and feeds it back to the computer in order that the fitness of circuit individuals can be calculated. We employed AD673 8-Bit A/D converter produced by Analog Devices Inc. ® to fulfill this work.

HBA. The main evolutionary algorithm unit, where Hereboy is performed to search for optimized circuit.

Pre-Evaluator. We employ some tricks of high speed pre-evaluate to find out the individuals which may present awful fitness or even injure the dpAsp chip. The program eliminates these individual from the download array and set their fitness to worst.

B. Results of Experiments

In order to investigate the effectiveness and performance of the intrinsic EHW HGS controller, we compare it with the well-designed conventional PID controller.

We run some experiments to test their robustness after setting a number of system parameters in order to ascertain the sensitivity of the control to parameter changes. Two groups of parameters are adopted as follows:

Group 1: T_y=0.05, T_w=1.6, T_a=8.5, e_x=1.7, e_y=1.12, e_h=0.86, e_{qx}=0.06, e_{qy}=1.4, e_{qh}=0.4.

Group 2: T_y=0.05, T_w=2.2, T_a=8.5, e_x=2.0, e_y=0.65, e_h=1.43, e_{qx}=0.15, e_{qy}=0.85, e_{qh}=0.18.

The parameters in group 1 and 2 are characteristic values of a turbine-generator set in different operating points. With group 1 we can get optimization control parameters of conventional PID and intrinsic EHW controller respectively. Then, corresponding to these parameters, we perform experiments with group 2. The result shows that, in a certain condition, both conventional PID controller and the EHW controller can achieve good performance. But when the system parameters are varied, the EHW controller can still keeps good performance while the conventional PID controller can not.

To test the dynamic performance, various disturbances are introduced into the system. The first kind of test is for load changing disturbance. This is an important design criterion which may provide an indication about the system stability. We applied a load change of 60% to the HGS and the time-domain responses were shown in Fig.6 and Fig.7.

Fig.6 recorded the dynamic curve of the conventional PID controller during the period of load change. We can see that the setting time is 18.4s and the overshoot is 1.28%. But in Fig.7 for intrinsic EHW controller, the setting time is 11.9s and overshoot is 1.03%, which shows the obvious superiority of dynamic performance for this kind of disturbance.

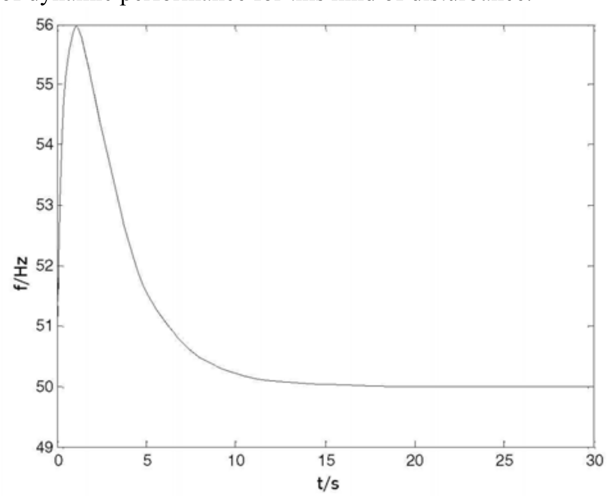

Fig.6 60% load change for conventional PID

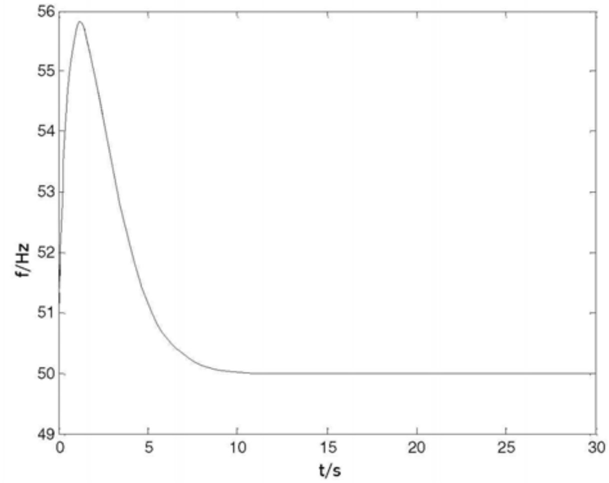

Fig.7 60% load change for intrinsic EHW controller

The second kind of test is for frequency disturbance. In the experiment, the frequency was switched form 55Hz to 59Hz and the corresponding response curves are obtained in Fig.8 and Fig.9. For conventional PID control in Fig.8, the setting time is 15.1s. However, in Fig.9, the setting time of the EHW controller is 8.6s.

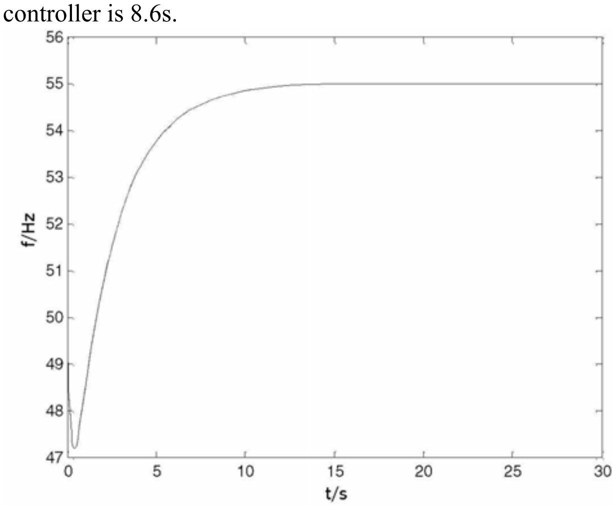

Fig.8 4Hz frequency disturbance for conventional PID

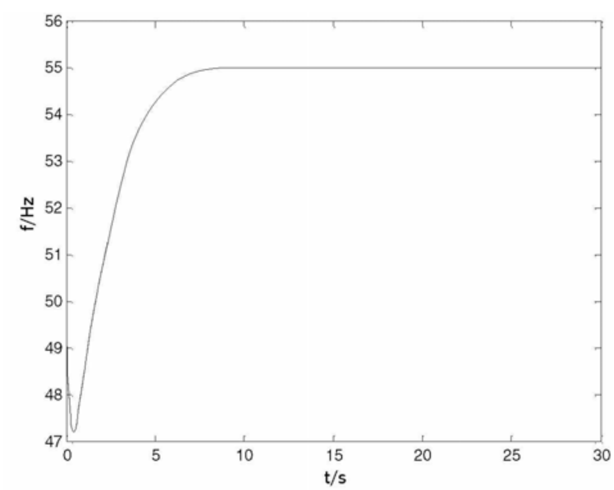

Fig.9 4Hz frequency disturbance for intrinsic EHW controller

VI. Conclusions

To apply intelligent method to improve the performance of practical industrial systems, we designed a HGS controller based on intrinsic evolvable hardware. This controller is implemented on ANEHP-Alpha, an intrinsic EHW platform based on the AN231E04 dpAsp device, which is in the latest generation of the Anadigm dpAsp FPAA series. We adopt Hereboy algorithm as the main evolutionary method with a fast pre-evaluation and bad individual elimination strategy to ensure the dpAsp devices against damage induced by illegal individuals. Comparing with the conventional PID, the EHW controller performs well on inhibiting the effects caused by the external disturbances with higher self-adjusting speed, smaller overshoot and lower sensitivity to parameters. The results of experiments show that the intrinsic EHW controller can improve effectively the robustness, stability and dynamic performance of HGS.

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