Genetic Algorithm Based PI Controller for Frequency Control of an Autonomous Hybrid Generation System

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***Abstract*— This paper presents an autonomous hybrid generation system consisting of wind turbine generators (WTG), a diesel engine generator (DEG), fuel cell (FC), a battery energy storage system (BESS) and an aqua electrolyzer (AE). The generated hydrogen by an aqua electrolyzer is used as fuel for a fuel cell. The power system frequency deviates for the sudden changes in load and generation. The output power of DEG, FC, BESS and power absorbed by AE is regulated by using controller such that frequency of the system is controlled. Controller used is proportional plus integral (PI). GA is used for optimization of controller gains of the proposed hybrid system. The system response with GA based controller is compared with that of classical method. Investigation shows that GA based controller gives better response than the classical method**

Keywords-Genetic Algorithm, Aqua electrolyzer, Fuel cell, Diesel engine generator, Battery energy storage system, Wind turbine generator.

NOMENCLATURE

Δf	System frequency deviation.
K_{sys}	Frequency characteristic constant of hybrid power system.
$G_{sys}(s)$	Transfer function of hybrid power system.
P_{DEG}	Output power of diesel generators.
$G_{DEG(s)}$	Transfer function of diesel generator.
K_{DEG}	Gain of diesel generator.
T_{DEG}	Time constant of diesel generator.
P_{FC}	Output power of fuel-cell generators.
K_{FC}	Gain of fuel cell.
T_{FC}	Time constant of fuel cell.
$G_{FC(s)}$	Transfer function of fuel-cell generators.
P_{BESS}	Input power to battery energy storage system.
$G_{BESS(s)}$	Transfer function of battery energy storage system.
K_{BESS}	Gain of battery energy storage system.
T_{BESS}	Time constant of battery energy storage system.
$G_{AE(s)}$	Transfer function of aqua electrolyzers .
P_{AE}	Input power to aqua electrolyzers.
K_{AE}	Gain of the aqua electrolyzer.
T_{AE}	Time constant of the aqua elctrolyzer.
P_S	Total power generation to the system.
P_L	Average power absorbed by loads.
ΔPe	Error in power supply and demand.
M	Inertia constant of the hybrid power system.
D	Damping constant of the hybrid power system.
P_{WTG}	Power output of wind generator.
$G_{WTG(s)}$	Transfer function of wind generator.
K_{WTG}	Gain of wind generator.
T_{WTG}	Time constant of wind generator.

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I. INTRODUCTION

In recent years the increasing concerns about the limited fossil fuel resources led to the awareness that the amount of energy import should be decreased so as to become less dependent of oil exporting countries. Further, the impact of fossil fuel on the environment, especially the global warming and the harmful effects of carbon emissions have created a new demand for clean and sustainable energy sources. Wind, sea, solar, biomass, geothermal powers are sustainable energy sources. Among these, solar energy has less power density whereas sea, biomass, geothermal powers have not yet been explored much to be considered as potential sources of energy. Wind assumes great importance and has the potential to make significant contribution.

Off-grid electricity can be generated by single source system such as using solar photovoltaic panels, wind turbine generators, micro-hydro plants, or fuel-powered combustion engine generator sets, or by combining two or more of these electricity generating sources in a so called hybrid system. The systems often include energy storage in the form of

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batteries. A hybrid system can supply power AC or DC or both. Component or system control or both is used to regulate the overall system operation. Various optimization approaches, such as, genetic algorithm, particle swam optimization, artificial neural network, are applied to optimize the gains of the controllers used in automatic generation control. These techniques have not yet been reported to apply in the field of hybrid energy systems for optimization of controller gains.

In [1,2] hybrid system studies proportional plus integral (PI) controller is used to regulate the output powers from distributed generation system to achieve power balance condition due to sudden variations in generation and load. The gain values of PI controller are chosen by trial and error method. In [10] the conventional PI controller has traditionally been tuned by the method described in Ziegler and Nichols. The controller gains once tuned for a given operating point are only suitable for limited operating point changes. Therefore, the use of the conventional PI controller does not meet the requirements of the robust performance [10]. Moreover, when the number of parameters to be optimized is large, conventional technique for optimization is certainly not preferred one. In this article, the genetic PI controller is designed based on a conventional controller's concept except that their gains are tuned on-line as operating point changes. The GA is finding widespread applications in systems optimizations. As an intelligent control technology the GA can give robust adaptive response with nonlinearity, parameter variation and load disturbance effect [3–5]. Basics of Genetic Algorithm are illustrated in [9]. The results of applying the genetic PI controller to the hybrid-power system are compared to those obtained by the application of a conventional PI controller. Simulated results show that the genetic PI controller provides improved dynamic performance than fixed gain conventional controller. The genetic controller also shows better transient performance for load disturbances.

II. PROPOSED HYBRID SYSTEM

The block diagram of the proposed hybrid system is shown in Fig.1.The system consists of wind turbine generators, diesel generator, fuel cell, aqua electrolyzer and battery energy storage system. The power supplied to the load is the sum of output powers from wind turbine generators, diesel generator, fuel cell and battery energy storage system. The aqua electrolyzer is used to absorb the fluctuations of wind turbine generator and produce the hydrogen gas which is used as input to fuel cell generator. The mathematical models with first order transfer functions for wind turbine system, fuel cell, aqua electrolyzer, diesel engine generator are shown in this section [6].

A. Wind Turbine Model

The output of wind turbine generator depends on the wind speed at that instant. The characteristic of wind turbine generator is illustrated in [1].

The wind turbine system contains several nonlinearities, which must be considered during system modelling. When a wind turbine uses its pitch controller to counteract utility grid frequency oscillations, its output power varies between

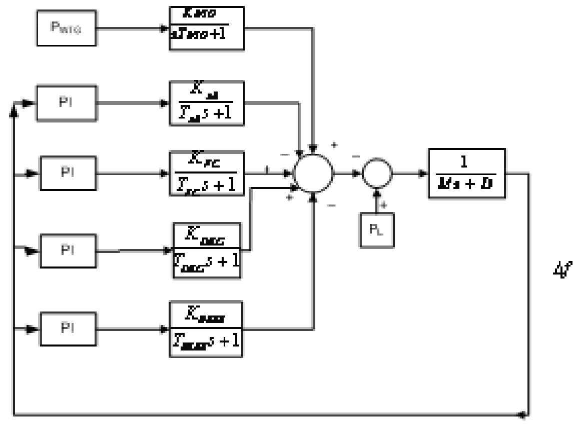

Fig.1. Block diagram of hybrid system

maximum, or rated power, and zero power. Hence, the pitch angle setpoint is nonlinearly limited by these boundaries. The pitch system, which turns the pitch angle according to wind speed, introduces a nonlinearity. The wind turbine can be simplified to a first order system. The transfer function of the WTG is represented by a first-order lag [6] as

$$G_{WTG}(S) = \frac{K_{WTG}}{sT_{WTG}+1} \quad (1)$$

Where K_{WTG} T_{WTG} are the gain and time constant of wind generator respectively.

B. Diesel generator

Diesel engine produces the torque, driving the synchronous machine generating the electrical power output. Because of sudden changes in load demands by the consumers, it is important that the diesel prime mover has a fast dynamic response and good capabilities of disturbance rejection.

A diesel generator is a nonlinear system because of presence of a nonlinear, time-varying dead time between the injection and production of the mechanical torque. The diesel generator is modeled by a simple first order transfer function given by [6]

$$G_{DEG}(S) = \frac{K_{DEG}}{T_{DEG}s+1} \quad (2)$$

where K_{DEG} and T_{DEG} represents the gain and time constant of diesel generator respectively.

C. Aqua electrolyzer

A part of the generated power from the WTG is sent to the AE to produce available hydrogen for the FC. The decomposition of water into hydrogen and oxygen can be achieved by passing the electric current between the two electrodes separated by aqueous electrolyte. The transfer function model of aqua electrolyzer can be expressed by [6]

$$G_{AE}(S) = \frac{K_{AE}}{T_{AE}s + 1} \quad (3)$$

where K_{AE} and T_{AE} are, respectively, the gain and time constant of the AE. Since a typical AE consists of several power converters, time constant of the AE is very small [7].

D. Fuel cell

Fuel cell generates power through the electrochemical reaction between hydrogen and oxygen. Fuel cell offer alternatives to conventional generators, such as diesel generators, that would allow power to be produced without noise or on-site pollutants. A typical fuel cell produces a small voltage. To create enough voltage, the cells are layered and combined in series and parallel circuits to form a fuel-cell stack. Fuel-cell developers claim a higher efficiency than traditional combustion technologies. The only drawback, as fuel-cell proponents concede, is that hydrogen is still more expensive than other energy sources such as coal, oil and natural gas.

Fuel cell generator is a higher order model and has non linearity. For low frequency domain analysis it is represented by a first order lag transfer function model given as [6]

$$G_{FC}(S) = \frac{K_{FC}}{T_{FC}s + 1} \quad (4)$$

where K_{FC} and T_{FC} represents the gain and time constant of fuel cell.

E. Battery energy storage system

The fluctuation of wind energy causes large problems for power systems operation. The consequence is that even though other energy sources can be saved by using wind energy, the short-term power fluctuation has to be secured by a conventional plant. A possible solution is storage of wind energy. Due to very good technical characteristics (large energy density, fast access time) the battery energy storage system has been an effective energy storage technology to store large amount of wind energy [8]. They can supply the system with a large amount of the power in a short time, or large amount of energy for a longer period. A higher power capacity can be achieved by connecting more modules. The transfer function model of battery energy storage system expressed by first order as [6]

$$G_{BESS} = \frac{K_{BESS}}{T_{BESS}s + 1} \quad (5)$$

where K_{BESS} and T_{BESS} are respectively, the gain and time constant of battery energy storage system

F. Power and frequency deviations

In order to provide good quality of supply to the consumers it is very important maintain the scheduled frequency under varying demand and supply conditions. Frequency can be maintained at desired level by maintain the active power balance between the generation and demand. A hybrid system with wind as one of the generating unit requires special control strategies because of highly fluctuating nature of wind. The strategies to be adopted to alleviate mismatch between generation and demand can either be by controlling the fuel to diesel electric power-generating unit or by rescheduling. The conventional approach normally uses a PI or PID controller. The use of GA based frequency control is more efficient method. In this paper power control strategy is obtained by difference between the power demand reference P_L and total power generation P_S.

$$\Delta P_e = P_S - P_L \quad (6)$$

Total power P_S is the sum of output power from wind turbine generators P_{WTG}, diesel generators P_{DEG} , fuel-cell generators P_{FC}, and negative input power to aqua electrolyzers P_{AE} and battery energy storage system. P_{BESS} given by

$$P_S = P_{DEG} + P_{WTG} + P_{FC} - P_{AE} \pm P_{BESS} \quad (7)$$

Because system frequency is changed with net power variation, the system frequency variation Δf is calculated by[6]

$$\Delta f = \frac{\Delta P_e}{K_{sys} + D} \quad (8)$$

where Ksys is system frequency characteristic constant of the hybrid power system. Since an inherent time delay exists between system frequency variation and power deviation, the transfer function for system frequency variation to per unit power deviation can be expressed by

$$G_{sys}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{sys}(1 + sT_{sys})} = \frac{1}{M_s + D} \quad (9)$$

where M and D are, respectively, the equivalent inertia constant and damping constant of the hybrid power system [6].

TABLE I
PARAMETERS OF PROPOSED HYBRID SYSTEM[6]

Gains	Time constants(sec)
K_{WTG}=1.0	T_{WTG}=1.5
K_{AE} =1/500	T_{AE}=0.5
K_{DEG} =1/300	T_{DEG} =2
K_{FC}=1/100	T_{FC} =4
K_{BESS} =-1/300	T_{BESS} =0.1

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TABLE II
PARAMETERS OF GA

Parameter	Value
Selection method	Roulette
Population size	20
Crossover probability	0.8
Mutation probability	0.01
Maximum no of generation	100

III. Simulation Results and Analysis

In this section, dynamic performances of the proposed hybrid system under consideration are presented for optimum gain settings of classical and GA based PI controller respectively. A simulation interval of 120 s has been chosen. To study the effect of generated wind power variation and load fluctuation following two cases as shown in table III, are considered.

TABLE III
SIMULATION CONDITIONS FOR EACH CASE

Case1	P_{WTG}=0.5 p.u at $0<t$ 40s & 0.4 p.u at $t>40$s and *P_L=1 at t 80s & 0.8 at $t>80$s*
Case2	P_{WTG}=variable and *P_L=1 at t 80s & 0.8 at $t>80$s*

F. *Time-Domain Analysis :case1*

In this case, during 0   t   40 s, the average wind power generated is kept 0.5 pu. and load demand is 1 p.u after 40s wind power generated suddenly dectreased to 0.4 p.u and at t=80 sec load is suddenly decreased from 1 pu. to 0.8 pu. The power system frequency fluctuates due to sudden changes in generated wind power and load demand. This deviation in frequency is controlled by the PI controller and the outputs of system components are automatically adjusted to corresponding values such that the error in supply demand and the deviation in frequency are minimum. The gain values of PI controller obtained through classical and GA technique and are given in TABLE IV.

TABLE IV.
GAINS OF PI CONTROLLER FOR EACH CASE

GAIN	CLASSICAL VALUE	GA VALUE
Kp1	-19.523	-54.33519
Ki1	-17.632	-51.70934
Kp2	67.487	46.28352
Ki2	42.22	16.98366
Kp3	70.2187	55.17631
Ki3	87.12	48.59286
Kp4	-1.245	-35.07284
Ki4	-12.89	-38.16234

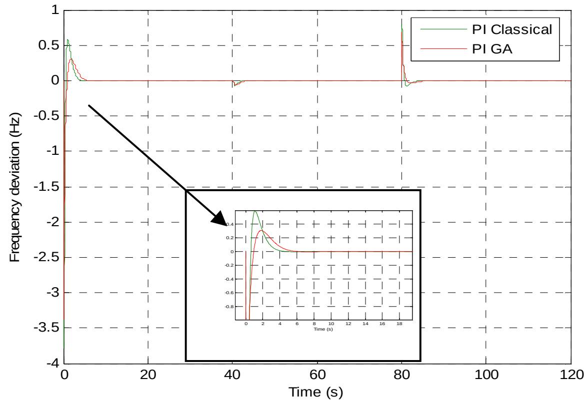

Fig.2. (a)

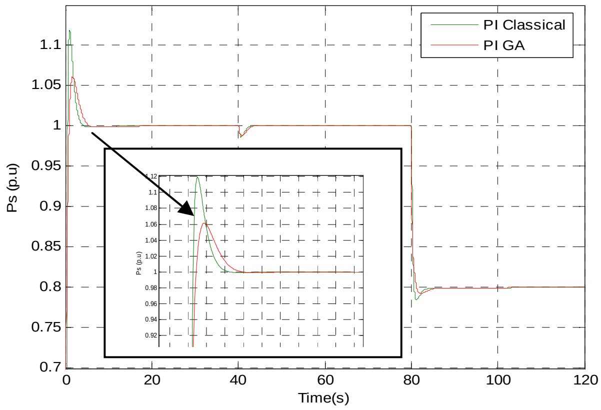

Fig.2. (b)

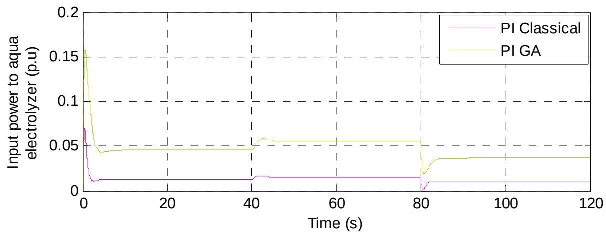

Fig.2. (c)

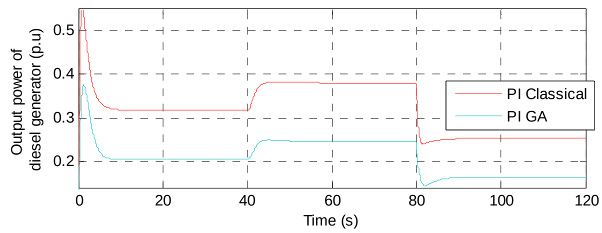

Fig.2. (d)

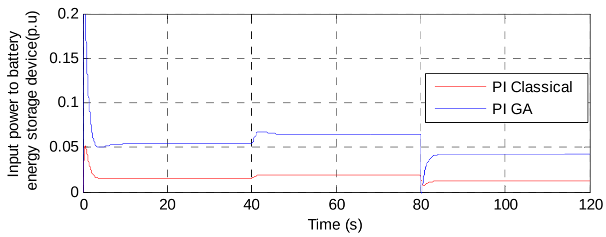

Fig.2. (e)

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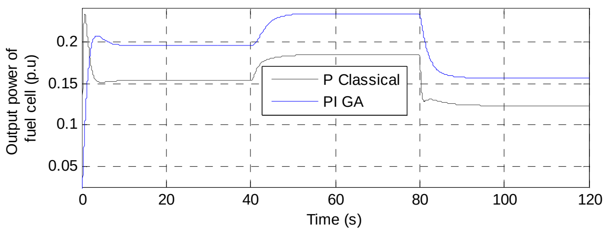

Fig.2. (f)

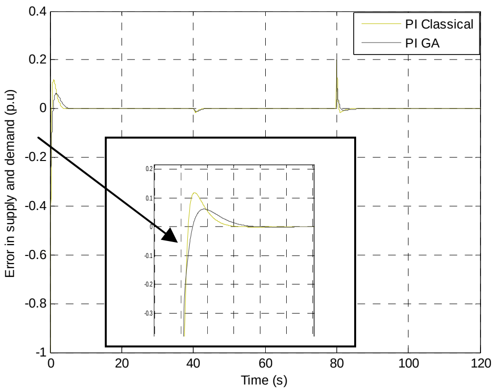

Fig.2. (g)

Fig.2. Simualtion results of proposed system (Case1). (a) Frequency deviation of power system Δ*f*. (b) Total power output P_s. (c) Input power to aqua electrolyzers $P_{AE.}$ (d) Output power of diesel generators P_{DEG} (e) Input power to battery energy storage system P_{BESS}. (f) Output power of fuel-cell generators $P_{FC.}$ (g) Error in power supply and demand ΔP_e.

G. Time-Domain Analysis :case2

In this study, we consider varying wind power [11] as shown in Fig. 3(a). A 20% step decrease in load occurs at t=80s. Simulation results are shown in Fig.3. (b)-(g).

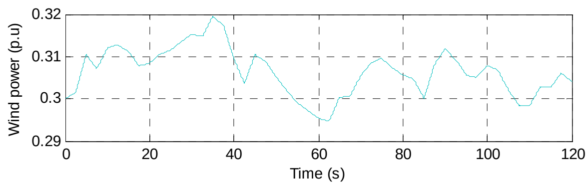

Fig. 3. (a)

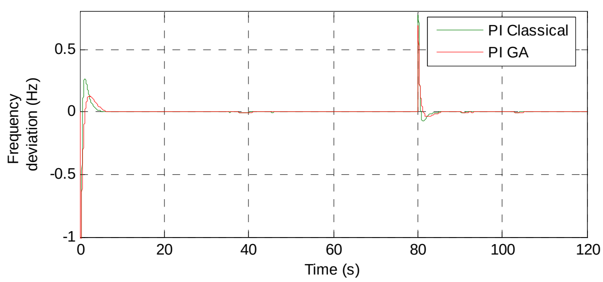

Fig. 3. (b)

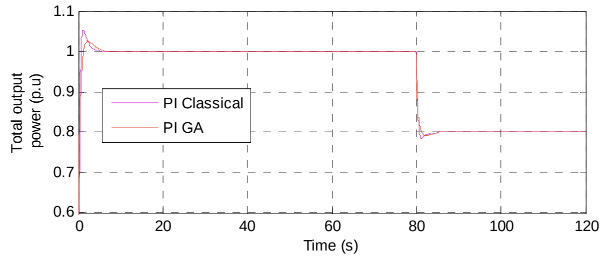

Fig.3. (c)

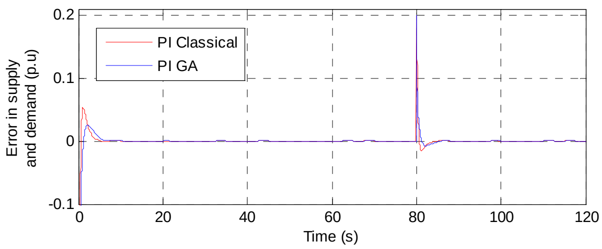

Fig. 3. (d)

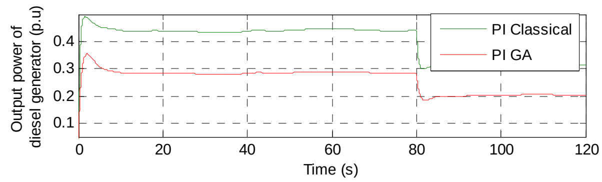

Fig. 3. (e)

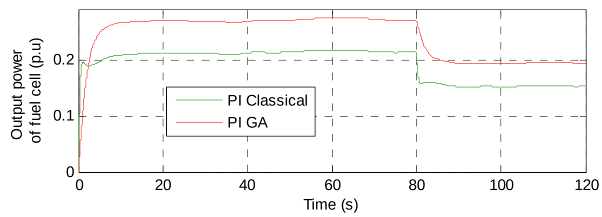

Fig. 3. (f)

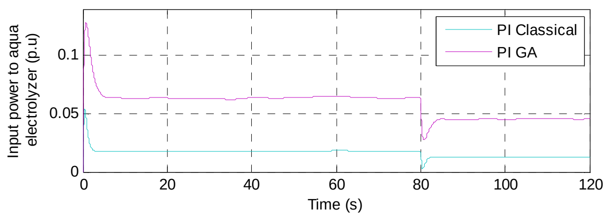

Fig.3. (g)

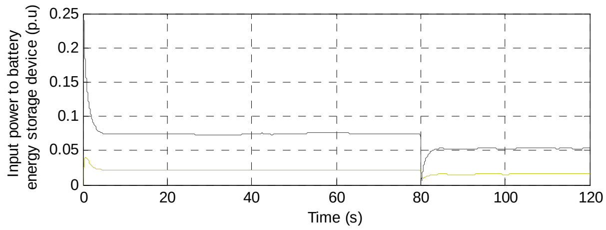

Fig.3. (h)

Fig.3. Simualtion results of proposed system (Case2) (b)Frequency deviation of power system Δ*f*. (c) Total power output P_s (d) Error in power supply and demand ΔP_e. (e) Output power of diesel generators P_{DEG} (f) Output power of

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fuel-cell generators $P_{FC.}$ (g) Input power to aqua electrolyzers P_{AE} . (h) Input power to battery energy storage system P_{BESS}.

H. Performance Analysis

During changes in load or wind power generation or both, frequency deviation is minimised by changing the generations of fuel cell, diesel generator, input power to aqua electrolyzers and input power to battery energy storage system. This has been achieved using PI controller. Controller is tuned through conventional method and GA respectively. Simulation result shows that GA based controller is better than conventional one in terms of peak deviation and settling time.

IV. Conclusion

The autonomous hybrid renewable energy power generation/energy system requires an automatic generation control system to eliminate the mismatch in supply and demand under varying condition of load and wind power. This paper presents models of an autonomous hybrid renewable energy power generation/energy storage system. In order to reduce the frequency deviation i.e., eliminate the mismatch in supply and demand under varying condition of load and wind power, the power flow from the distributed sources is regulated using PI controller. The gains of PI controller are designed by using classical method and GA. Performance of each controller is examined from dynamic behaviour in time-domain simulations of the system in isolated mode of operation. The simulation results show that GA-based optimization technique is much better to enable automatic generation control.

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