INVESTIGATIONS ON AUTO DISTURBANCE REJECTION CONTROLLER AND FUZZY CONTROLLER FOR MICROTURBINE BASED DISTRIBUTED GENERATOR

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Abstract- In recent electrical scenario, the power engineers have started to pay more attention to bridge the gap between generation and demand. Distributed Generation Technology has paved way for this task in recent decades. The micro-turbine generation system is regarded as one of the most promising ways of Distributed Generation. The micro-turbine is a complex thermal dynamic model. It is really a technical challenge to achieve accurate control because of its uncertainty and nonlinearity. In order to realize its steady control to the fullest extent, and its advantages among the Distributed Generation, researchers have started to focus on the performance of the Micro-turbine based systems at different operating conditions of the DG units. Hence they also attempt at designing an optimal controller for a Micro-turbine based DG unit. As a part of this research work, an Auto Disturbance Rejection Controller has been discussed in this project and its performance has been compared with Fuzzy controller.This paper deals with a 30kW micro-turbine and an analysis has been made on how an ADRC improves the stability of this system when compared to the PI and Fuzzy controllers. Load disturbance and short circuit are the two cases under which the performance analysis has been made in this work. MATLAB/Simulink software has been used to validate the superiority of the ADRC to the other controllers

Keywords: Micro turbine, auto disturbance rejection controller, modeling, robust research, load disturbance

I.   INTRODUCTION

Today's competitive energy market, concerns more about reliability, quality, and cost of the electric power. Many industries as well individual customers are opting to generate their own power rather than buying it from the grid. Round the globe, practice of meeting energy needs with decentralized or distributed generation (DG) is growing rapidly due to five major factors viz., technological advancement in DG technologies, and constraints on construction of new transmission lines, increased customer demand for highly reliable electric power, electricity market liberalization and concerns about environmental pollution. Most DG technologies are more efficient, reliable, and easy to own and operate. Main DG technologies include gas turbines, micro-turbines, wind turbines generator, fuel cells, photovoltaic cell (PV cell), etc. DGs come in different forms such as on-site gas or diesel fired turbines, reciprocating engines, micro-turbines, small hydro induction generators, wind turbines and fuel cells. Appropriate modeling of these DGs is needed in order to study their operation and impact on power systems. The micro-turbine (MT) generation system is a new developed thermal generator. It is because the characteristics of MT system are lower cost, higher efficiency, more reliability and convenience; it is regarded as one of the best promising ways of distributed generation and paid highly attention to. The relative researches have been done in modeling of micro-turbine system [1-3]. Reference [1] presents a six order model of the micro-turbine established by modular modeling method. A simple transferring function model is proposed in [2]. A simplified linear model is introduced by [3], which is based on the assumption that the operation point of the micro-turbine is close to the rated speed at all times. In that micro-turbine system's context, the research interests have been focused on the modeling so far, few papers are involved in the new controller design. The MT is a complicated system with nonlinearities and uncertainties. It is necessary to introduce control strategy with more robustness. An Auto Disturbance Rejection Controller (ADRC) based on Extended State Observer (ESO) is applied to the MT system. This project deals with the modeling and design of Auto disturbance rejection controller and fuzzy controller for a micro-turbine based DG unit comprising of a permanent magnet synchronous generator driven by a micro gas turbine, suitable for stand-alone operation. And also it presents the comparative study between classical PI, ADRC and Fuzzy controllers. Simulation results demonstrate the proposed ADRC has better adaptability and robustness than the classical PI and Fuzzy controller. Typical MT generation system is shown in Fig.1.1.
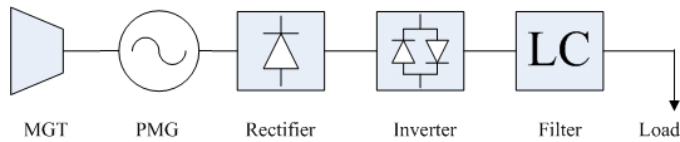
Fig.1. Schematic diagram of MT Generation system

Micro-turbines are small gas turbines which burn gaseous or liquid fuels to create a high energy gas stream that runs an electric generator. There is growing interest in the application of Micro-turbine Generation as they start quickly and are especially useful for peak power supply for grid support. Micro-turbines are small high speed gas turbines that produce power in the range of 25 kW to 500 kW. They operate on the same principle of conventional gas turbines.

The technical and manufacturing developments during the last decade have encouraged the utilization of micro-turbines in many applications including their utilization as DG units. The advantages of using micro-turbine are low installation and infrastructure requirements, low maintenance cost, compact size, light weight than other engines with the same capacity, fuel edibility, high efficiency, etc. The availability of micro-turbines is well suited for small commercial buildings, peak saving, standby and emergency power. Most of the methods of construction of micro-turbines are based on a single-shaft design to rotate at high speed in the range of 50000 to 120000 rpm. Hence, high speed permanent magnet generator (PMG) is used to produce AC power at high frequencies.

There are mainly two types of micro-turbine systems available viz., single-shaft models and two shaft models. In single-shaft designs, a single expansion turbine is coupled with both the compressor and the generator. As a result they operate at high speeds, some at the rate of 100,000 rpm, and generate electrical power at high frequencies (in the order of kHz). Two-shaft models, on the other hand, use a turbine to drive the compressor on one shaft and a power turbine on a separate shaft connected to a conventional generator via a gear box which generates AC power at 60 Hz or 50 Hz. In a single-shaft design, since the generator provides a high frequency AC voltage source, a power electronic interface between the MTG system and the AC load is required. For a two-shaft design, on the other hand, there is no need for such interface.

II.   MICROTURBINE GENERATION SYSTEM MODEL

Micro-turbines are small gas turbines coupled with generators. Today's micro-turbine technology is the first of the development work in small stationary and automotive gas turbines, pursued by the automotive industry which started its development in 1950's. The range of micro-turbines available is 25 kW to 500 kW, while conventional gas turbines size range from 500 kW to more than 300 MW. Micro-turbines generally have lower electrical efficiency than similarly sized internal combustion (IC) engines. However, due to design

simplicity, high reliability, lower noise and vibration, and significantly lower (up to 8 times lower than diesel engines) emissions, Micro-turbines have attracted the market. Micro-turbines are primarily designed to operate on natural gas, but can also use other liquid and gaseous fuels like, kerosene, landfill gas, biogas, etc. A micro-turbine can also be equipped with recuperator to improve electrical efficiency. The MTG systems are gaining popularity in distributed power generation because of their smaller size, ultra low emissions, high efficiency, etc. There is a growing interest in the application of MTGs as they can start quickly and are especially useful for on-peak power supply for grid support. Other applications include remote power and combined heat and power (CHP) systems by utilizing the heat contained in the exhaust gases to supply thermal energy needs in a building or industrial processes.

In a typical micro-turbine, the inlet air is compressed in a radial (centrifugal) compressor, and then preheated in the recuperator using heat from the turbine exhaust. The expanding gas has roughly the same basic physical properties, temperature-pressure relationship, expansion speed, etc., whether enclosed in a small or a large turbine chamber. Therefore, tips of the turbine blades in any efficient gas turbine generator must move at a speed appropriate to capture energy from the expanding gas. This means, the utility turbines with 8 feet diameter turbine wheels can spin at only 1500 or 3000 rpm, while the micro-turbines with wheel only 3-4 inches diameter would run at high speed. The rotational speed of the commercially available micro-turbine ranges from 50,000 rpm to 1, 20,000rpm.

The microturbine is a complicated thermal dynamic model. It is not realistic to build the exact model because of the existence of nonlinearities and uncertainties. If it is assumed that the microturbine is operated at all times close to its rated speed, and the start up and shut down processes are ignored at the same time. A simple model can be built [3] as it is shown in figure 2. The assumption can help to the simulation. But ignoring some conditions can increase the uncertainties of the model at the same time. So it is necessary to introduce more effective controller to reduce the impact caused by uncertainties, for example Auto disturbance rejection controller. The microturbine is a complicated thermal dynamic model. It is not realistic to build the exact model because of the existence of nonlinearities and uncertainties.

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goes back to normal situation. Because the microturbine is mainly governed by speed control, the ADRC is only applied to the speed control. The temperature is still regulated by classical PI controller. The exhaust temperature function *f1* and torque function *f2* is given by

$$f_1 = T_R - 700(1 - W_f) + 550(1 - \omega) \tag{1}$$

$$f_2 = 1.3(W_f - 0.23) + 0.5(1 - \omega) \tag{2}$$

Where ω denotes turbine speed, *Wf* denotes fuel flows signal, *TR* denotes exhaust temperature. The torque function is accurate to within 5 percent at part load, and is significantly accurate at rated value. The exhaust temperature function is somewhat less accurate at part load. But it is only active at the design point, and the impact of the part load inaccuracy can be ignored [3].
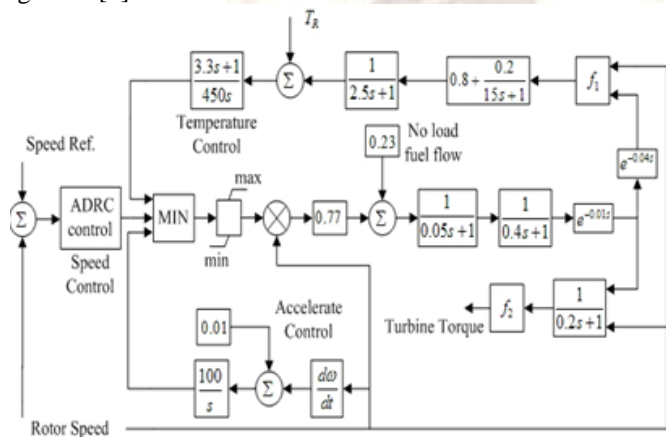
Fig.2 Microturbine model

B. Permanent magnet generator model

The difference between permanent magnet generator (PMG) and common synchronous generator is the PMG uses permanent magnet to excite. Reference [5] gives a detailed model of PMG. The rectifier is used to convert the high frequency alternating current to direct current. Its detail model is shown in full particulars in reference [6].The same as PMG, the rectifier is considered as an uncontrollable module. Simplifications can be applied to the modeling. If assumed that the damp torque is ignored, integrative model of the PMG and rectifier can be built as follows[7]:
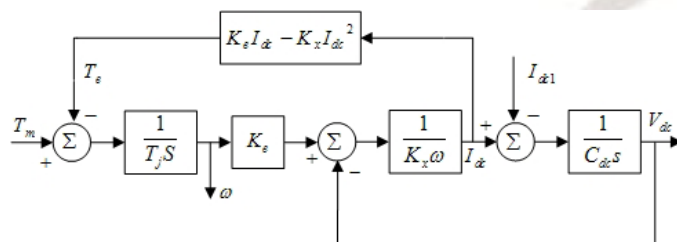

Fig.3 integrated model of PMG and rectifier

The rotor motion equation of the PMG can be expressed as:

$$\frac{d\omega}{dt} = \frac{1}{T_j}(T_m - T_e) \tag{3}$$

Where *Tm* denotes turbine torque; *Te* denotes electrical torque; *Tj* denotes the mechanical inertia constant of the rotor.
The line-to-line voltage of the PMG can be expressed as:

$$V_{LL} = V_m \sin(\omega t) = K_v \omega \sin(\omega t) \tag{4}$$

Where *Vm* denotes peak value of the generator; K_V is the voltage constant. When considering the phase changing process, the output voltage of three-phase full wave bridge can be expressed as:

$$V_{dc} = \frac{3}{\pi} V_m - \frac{3\omega L_B}{\pi} I_{dc} \tag{5}$$

Where *LB* denotes the leakage inductance of the generator stator windings, *Vdc* denotes the direct voltage of the DC side, and *dc* denotes direct current.
Combine equations (4) and (5), a new equation can be written as:

$$K_e \omega = V_{dc} + K_x \omega I_{dc} \tag{6}$$

According to equation (4) and (5), constants *Ke* and *Kx* can be defined as:

$$K_e = \frac{3K_v}{\pi}, \quad K_x = \frac{3L_B}{\pi}$$

Electromagnetic power can be expressed as:

$$P_e = V_{dc} I_{dc} = K_e \omega I_{dc} - K_x \omega I_{dc}^2 \tag{7}$$

Assuming *Cdc* denotes smoothing capacitance of the DC side, and *Idc1* denotes the input current of the inverter, The DC side can be expressed as:

$$I_{dc} - I_{dc1} = C_{dc} \frac{dV_{dc}}{dt} \tag{8}$$

If ignoring the loss of the rectifier, the electromagnetic torque can be expressed as:

$$T_e = \frac{P_e}{\omega} = K_e I_{dc} - K_x I_{dc}^2 \tag{9}$$

Simple model of the PMG and rectifier is shown in figure 3.

C. Inverter model

The inverter is used to convert direct current to alternative current. When running in parallel with the power grid, the grid

itself fixes the frequency. Fixed power control is used to control the power transmission. On a stand-alone system, the frequency will be defined by the load. We can apply a voltage control to the inverter, and the inverter real and reactive power will be defined automatically [8]. This paper researches on the stand-alone system and applies plus width modulation (PWM) to the inverter. The voltage is regulated at 380V by classical PI controller. The filter is used to eliminate the harmonic generated by the inverter. In order to make simulation easily and further research on the system running parallel with the power grid, the paper directly applies the IGBT inverter in MATLAB's SimPowerSystems demons. In the simulation, a controlled voltage source is used to connect the inverter with the rectifier output. The detailed model and its control strategy are presented in reference [9].

III Fuzzy Controller

The micro-turbine is a complex thermal dynamic model. It is impossible to achieve accurate control because of uncertainty and nonlinearity. In order to realize its steady control and fully exert its advantages among the Distributed Generation, the fuzzy control is introduced. The components of single shaft gas turbine modeled include speed control, temperature control and fuel system. Among the three controllers, speed control is the main heart of the micro-turbine model. Here fuzzy controller can be adopted to speed control loop. Fuzzy based control for microturbine discussed [].

IV. ADRC CONTROLLER

The ADRC is a nonlinear robust control technology based on process error. On the basis of the state error and its orientation, the ADRC takes feedback control through nonlinear structure, uses ESO to observe system state variables and impact caused by the internal and external interrupts, and transforms the controlled object to simple serious connection integral system [10]. The ADRC is made up of tracking differentiator (TD), extended state observe, nonlinear state error feedback (NLSEF) [11]. The schematic diagram of ADRC is shown in figure 4.
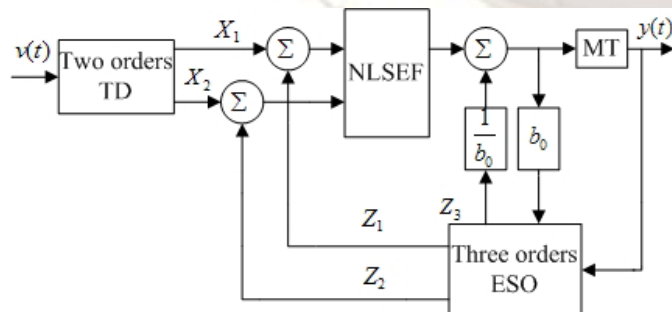

Fig.4 schematic diagram of ADRC

A. Tracking differentiator

Reference [12] gives three types of TD. The paper introduces the two orders TD. In order to avoid oscillation near origin, the sign function sign is changed into linear saturation function sat. An effective two order is expressed as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -R_t \, sat\left(x_1 - v(t) + \dfrac{|x_2|x_2}{2R_t} \right) \end{cases}$$

Where

$$sat(A,\delta) = \begin{cases} sign(A), |A| > \delta \\ \dfrac{A}{\delta}, |A| \le \delta, \delta > 0 \end{cases}$$

B. Extended state observer

When using the ordinary ESO in feedback control, it is always necessary to build more accurate model. It is limited when applying to the MT system because of its uncertainties and nonlinearities. However, the accurate model of the MT system is not necessary when using the ESO of ADRC. There is no need to distinguish between certainty and uncertainty, linearity and nonlinearity, time-invariant system and time-varying system. We only need the model inputs and outputs to estimate the real time state; the dynamics of the MT that is beyond modeling and the impacts caused by external interrupt [13]. The two orders ESO is described as:

$$\begin{cases} \varepsilon = z_1 - y \\ \dot{z}_1 = z_2 - \beta_1 \varepsilon \\ \dot{z}_2 = z_3 - \beta_2 \, fal(\varepsilon, \dfrac{1}{2}, h) + bu \\ \dot{z}_3 = -\beta_3 \, fal(\varepsilon, \dfrac{1}{4}, h) \end{cases}$$

Where

$$fal(\varepsilon,\alpha,\delta) = \begin{cases} |\varepsilon|^\alpha \, sign(\varepsilon), |\varepsilon| > \delta, \\ \dfrac{\varepsilon}{\delta^{1-\alpha}}, |\varepsilon| < \delta. \end{cases}$$

Nonlinear state error feedback

Classical PID controller uses linear state error to compute the controlled variables. This always brings on conflict between fastness and overshoot. So the paper introduces nonlinear state error feedback expressed as:

$$u_1 = \beta_{01} fal(\varepsilon_0, \alpha_0, \delta) + \beta_{02} fal(\varepsilon_1, \alpha_1, \delta) + \beta_{03} fal(\varepsilon_2, \alpha_2, \delta) \tag{4.10}$$

V. SIMULATION

The researches focus on simulation of load disturbance and short circuit fault. The paper compares ADRC & Fuzzy with classical PI controller applied to the MT system. Simulation

results show the proposed controllers has better adaptability and robustness than the classical PI controller. It can improve the stability of the microturbine.

A. Parameters

The parameters of classical PI controller applied to the speed control are as follows: KI=1.1, KP=12.5. The parameters of Auto disturbance rejection controller are as follows: $\beta1$=1, $\beta2$=500, $\beta3$=50, b=20; $\beta01$=0.1, $\beta02$=5, $\beta03$=0.3, $a0$=0.5, $a1$=0.8, $a2$=0.6, Rt=60, δ=0.001. These parameters are adjusted by repeating debugging.

B. Simulation of load disturbance

The rated capacity of the MT system is 30kW. The MT Generation system first operates at half of the capacity, then the load increase to its rated value at t=15 seconds. And at t=25 seconds it comes back to 0.5 p.u. load. Figure 5 shows the simulation results of the mechanic torque Tm, the fuel flow Wf, the rotor speed ω. Obviously, both the two controllers can stabilize the system. But the proposed controller can improve the stability of the system. Not only the regulating time is shorter, but also the overshoot is smaller. The microturbine can operate at all modes more smoothly.
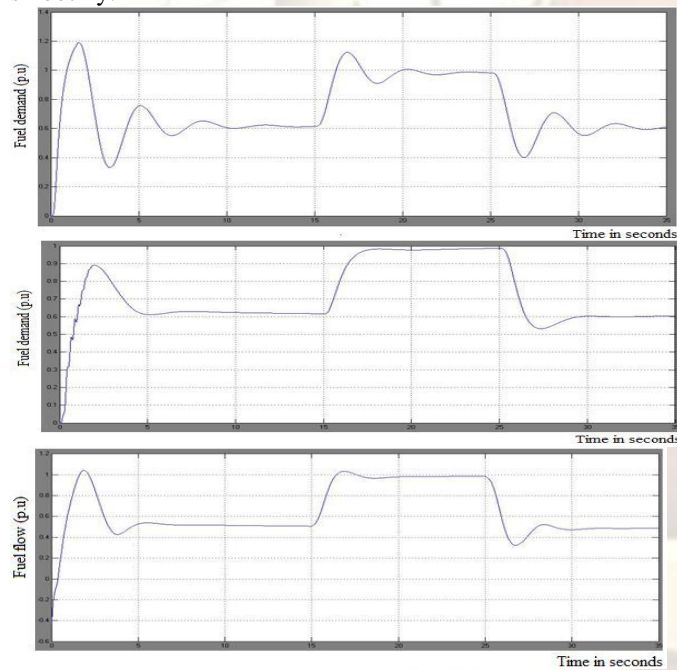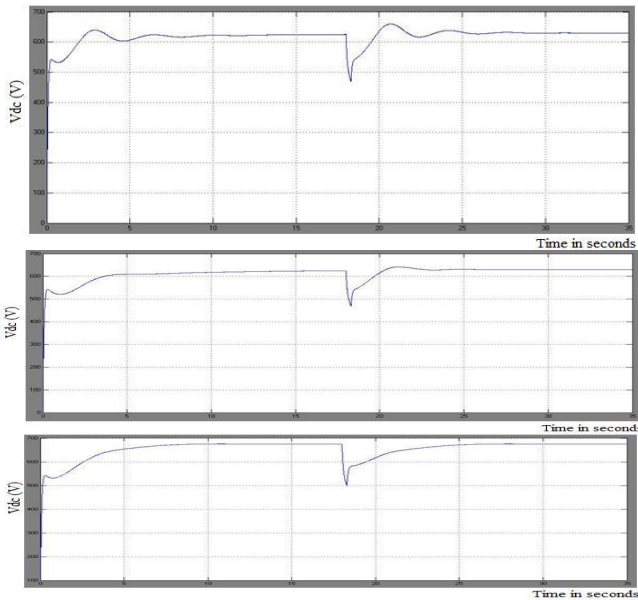

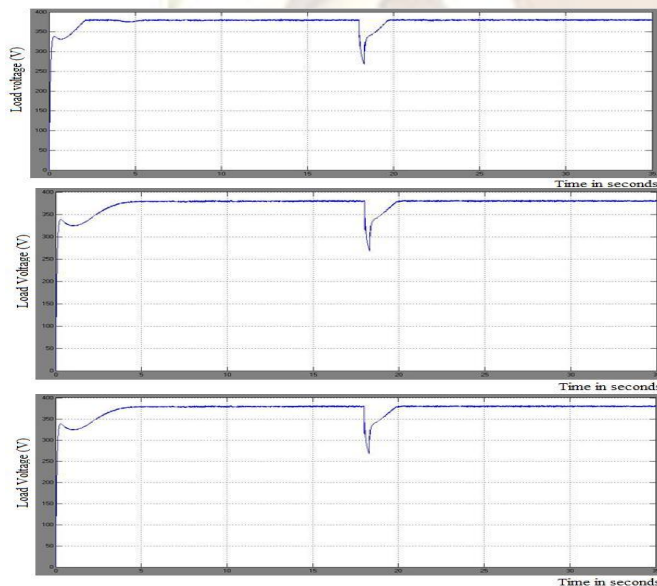**Fig.5.1: Fuel demand signals by using PI, ADRC and Fuzzy controllers**
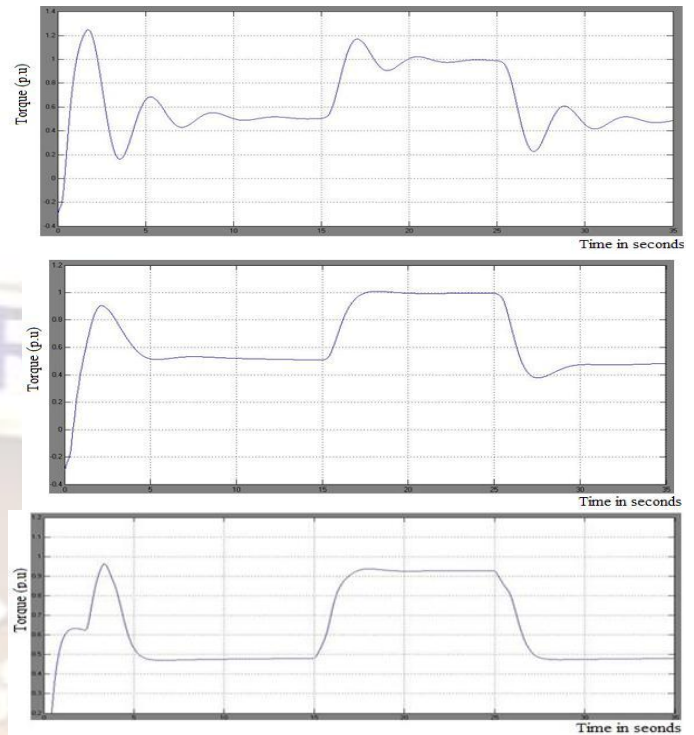
Fig.5.2 Torque signals by using PI, ADRC& Fuzzy Controller
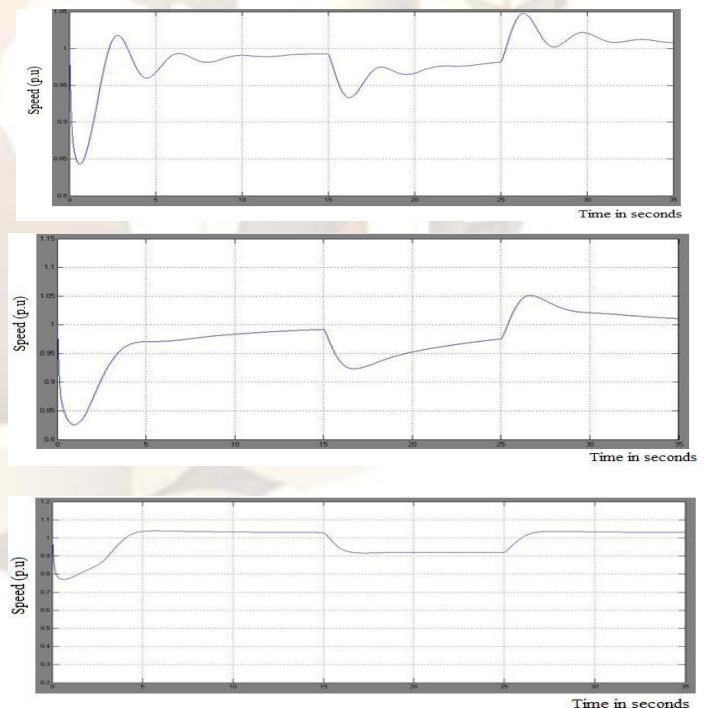
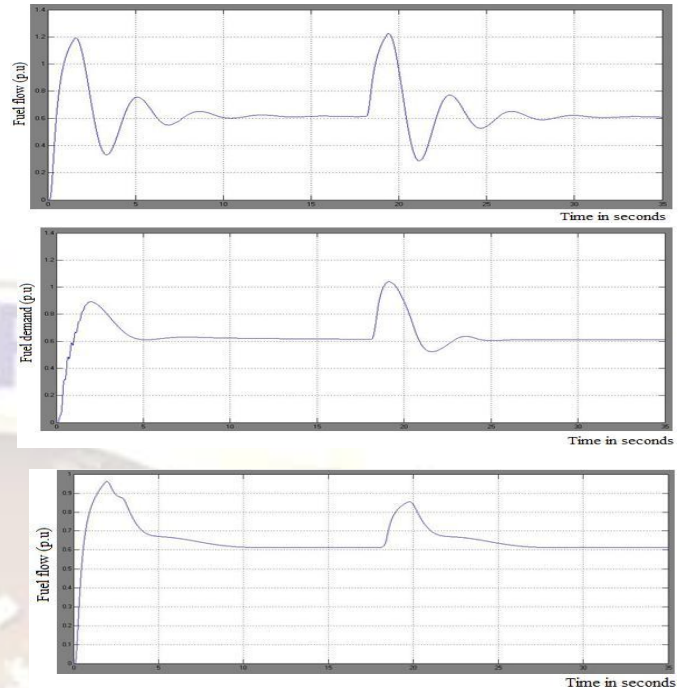**Fig.5.3:Speed signals by using PI,ADRC & Fuzzy controllers**

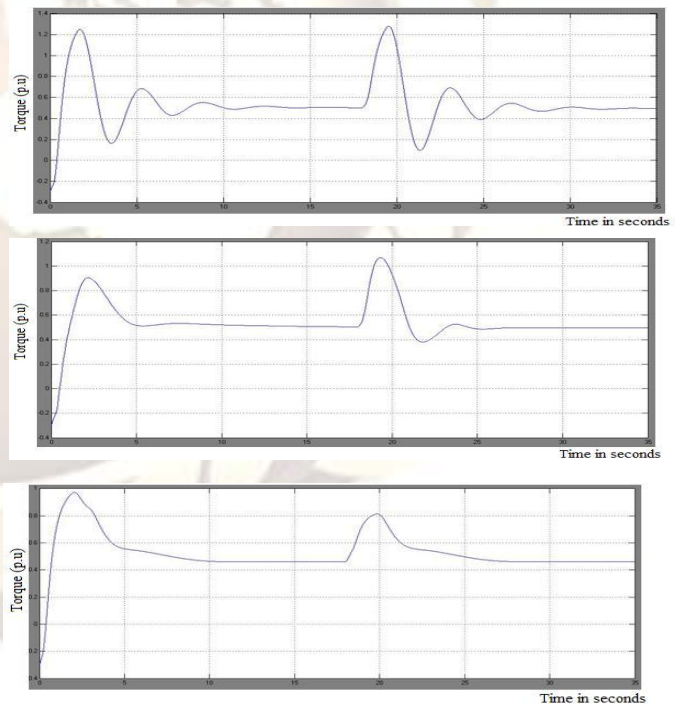**Fig.5.10 DC Voltages by using PI, ADRC & Fuzzy controllers**

Fig.5.12 Load voltages by using PI, ADRC & fuzzy Controller

C. Simulation of short circuit

Before the short circuit fault happens, the MT system operates at half rated load point. The fault happens at t=18seconds and lasts 0.3 seconds. Figures below shows the simulation results of the mechanical torque (Tm), the fuel flow (Wf), the rotor speed (ω), direct current (I_{dc}), direct voltage (V_{dc}) and Load voltage (V_{ab}), by using PI, ADRC and Fuzzy controllers.
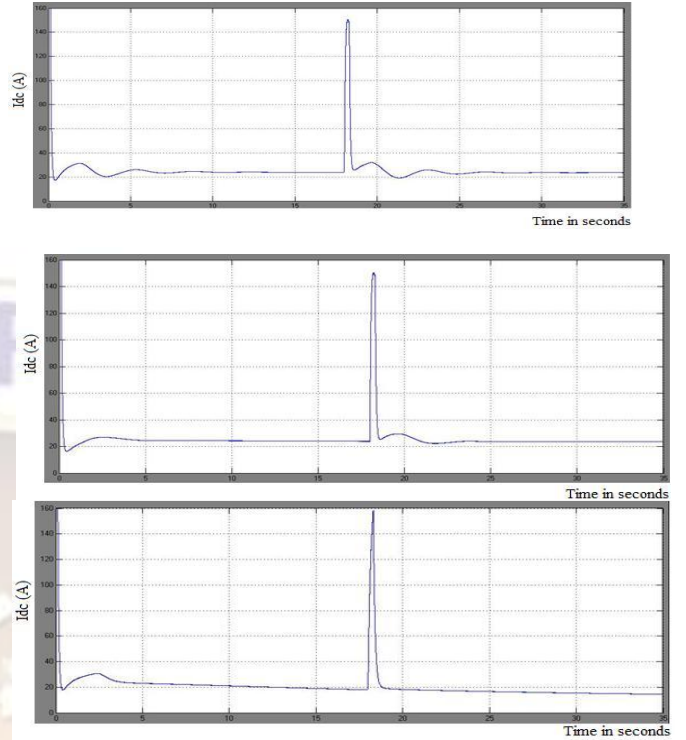

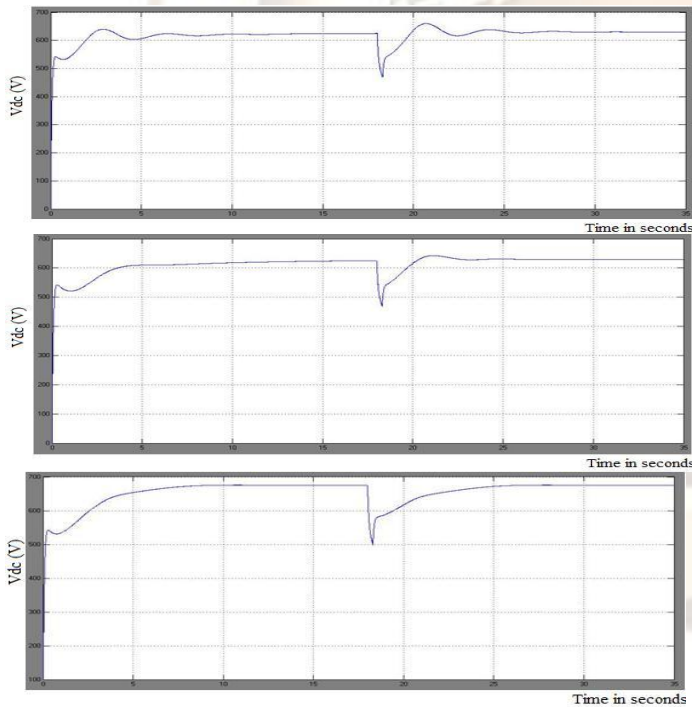**Fig.5.7: Fuel demand signals by using PI, ADRC and Fuzzy controllers**

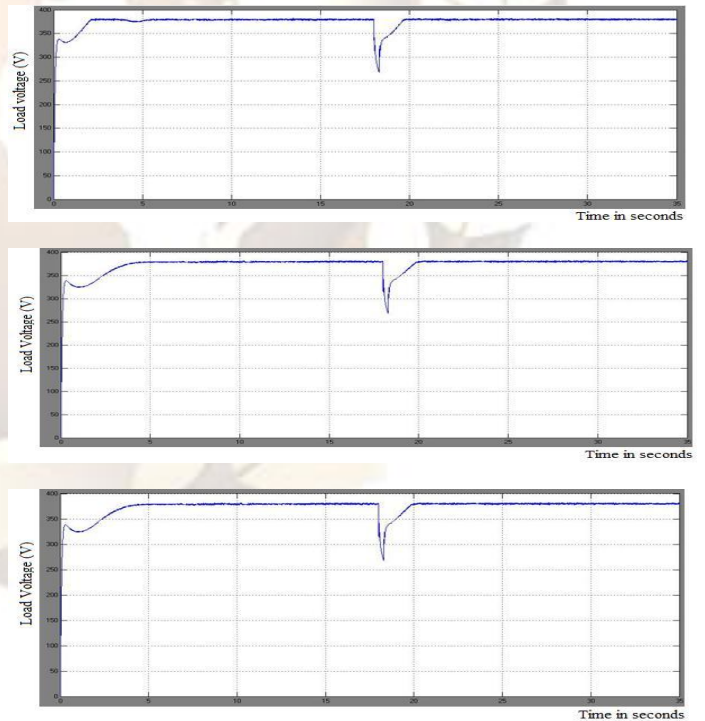**Fig.5.8: Torque signals by using PI, ADRC and Fuzzy controllers**
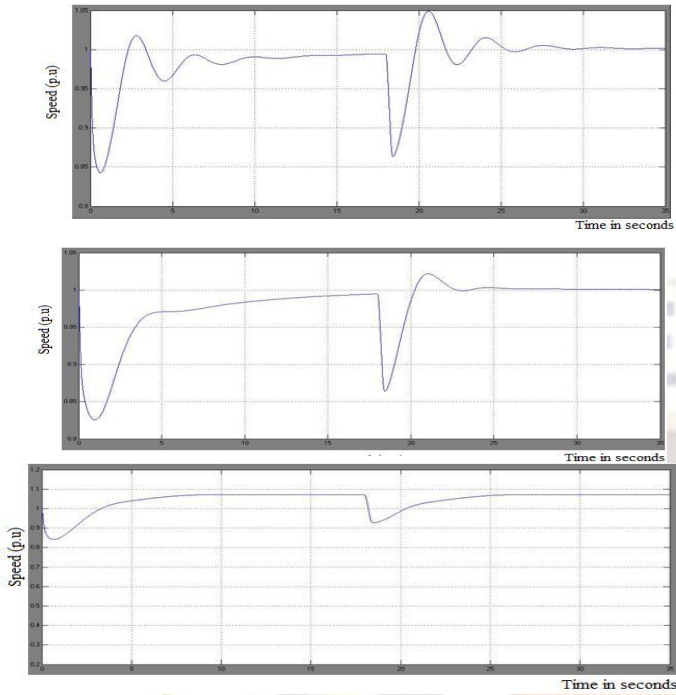
Fig.5.9: Speed signals by using PI, ADRC and Fuzzy controllers

Fig.5.11: DC Currents by using PI, ADRC and Fuzzy controllers

Fig.5.10: DC Voltages by using PI, ADRC and Fuzzy controllers

Fig5.12 Load voltages by using PI, ADRC & Fuzzy controllers

Simulation models for speed control of micro-turbine by using PI, ADRC and Fuzzy controllers have been developed. Obviously, three controllers can stabilize the system. But the ADRC controller improves the stability of the system. Apart from the regulating time becoming shorter, the overshoot is also smaller. When steady state is violated, it can settle at another point faster. Especially speed can be controlled such as to be maintained at rated speed. The ADRC controller is found to improve the performance of the Micro-turbine at all modes (i.e. load disturbance and short circuit simulation) in a smooth manner).

VI. CONCLUSION

Distributed Generation (DG) technologies are expected to play an important role in future power systems. In this work the integrative model of the MT generation system has been explained in detail, and a comparison of the ADRC and Fuzzy controllers with the classical PI controller has been discussed. The superiority of the ADRC has been validated using MATLAB simulation. The detailed simulation model of the Micro-turbine (MT) generating system with fuzzy controller and ADRC controller has been developed using Matlab/simulink package. The Auto disturbance rejection controller observes the external interrupt effectively, and compensates via nonlinear state error feedback. It is found to restrain the speed error of the MT and increase the response time, and maintain a small overshoot at the same time. When load disturbance happens, the ADRC keeps the micro-turbine system rapidly transfer to a new static state. Especially during the simulation of short circuit fault, the ADRC shows great adaptability and robustness. The simulation results show that the developed model of the MTG system has the ability to adjust the supply as per the power requirements of the load, within MTG's rating.

VI. ACKNOWLEDGEMENT

VII. REFERENCES

[1] Zheng LI, De-hui WANG, Ya-li XUE, et al, "Reasearch on ways of modeling of micro-turbine (part 1): Analysis of dynamic characteristic," *Chinese Journal of Power Engineering, vol.25,pp. 13-17, Feb.2005.*

[2] Robert Lasseter, "Dynaic models for micro-turbines and fuel cells," in 2001 *Power Engineering Society Summer Meeting, pp.761-766.*

[3] Rowen W. J., "Simplified mathematical representation of heavy duty gas turbines," *ASME Journal of Engineering for power, vol.105, pp. 865-869, Jul0 1983.*

[4] V.V Vadher, I.R. Smith, B. A. Fanthome, "Simulation of permanent magnet generator/rectifier combinations," *Aerospace and Electronic System, vol.22,pp. 64-70, jan.1986.*

[5] Chang-liang XIA, Zhan-feng SONG, "Pitch control of variable speed constant frequency wind turbines based on active-disturbance rejection controller," *Proceedings of the CSEE, vol. 27, pp.91-95, May.2007.*

[6] Jing-qing HAN, "Auto disturbance rejection control technique," *Frontier Science*, vol. 1, pp.24-31, Jan. 2007.

[7] Jinq-qing Han, Wei Wang, "Nonlinear tracking differentiator," *Journal of System Science and Mathmatic Science, vol. 14, pp.177-183, Feb.1994.*

[8] Jia-Peng Tong and Tao Yu, "Nonlinear PID control Design for Improving stability of Micro-turbine systems", *DPRT 2008.6-9 April 2008 Nanjing, China.*

[9] Tao Yu and Jia-Penq Tong, "Auto Disturbance Rejection Control of Micro-turbine system", *vol. 1, pp.24-31, jan.2008*

[10] H. Nikkhajoei and M.R.Iravani, "Modeling and analysis of a microturbine generation system," *IEEE Power Engineering Society Summer Meeting, vol .1, pp. 167 -169, 2002.*

[11] A. Bertani, C. Bossi, F. Fornari, S. Massucco, S. Spelta, and F. Tivegna, "A micro-turbine generation system for grid connected and islanding operation," in *Proc. IEEE Power Systems Conference and Exposition*, vol. 1, Oct. 2004, pp. 360-365.

[12] A. Al-Hinai, A. Feliachi, "Dynamic Model Of A Micro-turbine Used As A Distributed generator," *in Proceedings, 34th Southeastern Symposium on system Theory*,Huntsville,pp.209-213, Alabama, March 2002.

[13] D. N. Gaonkar and R. N. Patel, "Modeling and simulation of micro-turbine based distributed generation system," in Proc. IEEE Power India Conference, New Delhi, India, Apr. 2006, pp.256-260.

[14] G.Chen, "Conventional and fuzzy PID controllers an overview," Int.J.Intell.control syst., vlo.1, pp.235-246, 1996.

[15] Jan Jantzen, "Design of Fuzzy Controllers". M.J.Hossain, M.A.Hoque, M.A.ali, M.A.Rahman, "Fuzzy-logic-based Control for Induction Motor Drive with the consideration of core loss", *4th International Conference on Electrical and Computer Engineering ICECE 2006, 19-21 December 2006, Dhaka, Bangladesh*