# An Improved Model-based Controller for Power Turbine Generators on Grid system of Shipboard

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## ABSTRACT

The purpose of this paper is to present a fuzzy based model reference adaptive controller for a waste heat recovery generation system using Power Turbine Generators (PTGs) on a shipboard grid system. The PTG system is a waste heat recovery type generation making use of exhaust gas from main shipboard diesel engines. Marine propulsion of the ship can be generated by means of main diesel engine. Onboard power management is one of the main issues in ships. For efficient management of onboard power supply PTG extract part of the exhaust gas from the main diesel engine. The speed control, however, is difficult to keep in place because of fouling conditions and propulsion speed variations across time. The Fuzzy based MRA controller for exhaust gas turbine of an Electric Shipboard Power System is designed. The performance of the speed is controlled. The proposed controller is evaluated and it is compared with the conventional controller and model reference adaptive controller by using MATLAB simulink.

## Keywords

Fuzzy Logic, Model Reference adaptive control (MRAC), marine equipment, system identification, adaptive control, ship, waste recovery, diesel engines, control systems, frequency control.

## 1. INTRODUCTION

On-board power requirements for large merchant ships such as container ships and oil tankers are typically met by systems is composed of a diesel generator (DG), a steam turbine generator (TG), and a shaft generator (SG) installed on the propeller shaft. The main on-board power supply is a DG that uses fossil fuels. Recent hikes in fuel prices have warranted further improvements in fuel economy on shipboard systems. Propulsion can be accomplished by means of main diesel engines, steam turbines, gas turbines, electrical propulsion, and so forth, although main diesel engines are used for the majority of the world’s vessels.

One arrangement that has drawn attention is a power turbine that extracts part of the exhaust gas from the main diesel engine. [3]. Output from the main diesel engine, i.e., the drive source for the propulsion, is affected by demands for the vessel speed as well as the need to balance propeller speed against relevant sea conditions, meaning that such output is not constant. In this respect, the quantity of state for the exhaust gas collected in the manifold after combustion in the cylinders changes in accordance with engine output [4].

Each power source needs to control the frequency by using droop method controller. A single operation was considered difficult for the PTG system at the design stage because it is difficult to control the frequency of the electrical system using valves in the gas system. An on/off-type valve with a pneumatic actuator is used to realize the low-cost facility.

Moreover, since the exhaust gas contains considerable amounts of ash and soot, the valve-type selection is limited to the use of a butterfly type valve. Valve operation speed is in the range of 0.5–1.0 s, imposing an extreme delay on frequency control [4].

The valve based control is made more difficult because the amount of exhaust gas from the main diesel engine as a power source needs to be kept constant to reduce the influence on the engine.

This paper deals with the conventional model reference adaptive control (MRAC) and replaces conventional control technique with fuzzy based model reference adaptive control scheme. The Model Reference Adaptive Control (MRAC) speed control systems do not achieve consistent satisfactory performance. The fuzzy logic model reference adaptive control maintains satisfactory response of speed.

# 2. POWER TURBINE GENERATOR SYSTEM AND MODEL

## 2.1 Marine plant with PTG

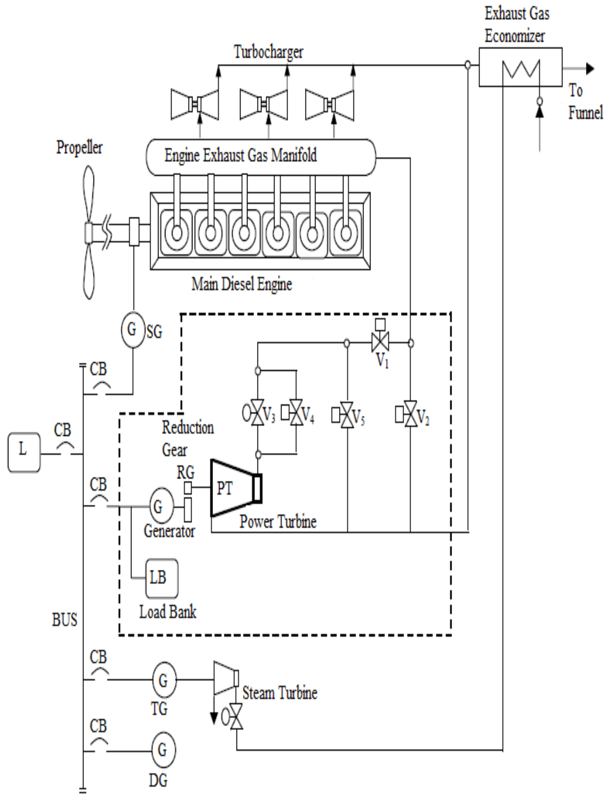

**Fig. 1. Outline of the power system for a marine plant with PTG**

Fig. 1 shows the power system for a marine plant. CB is the circuit breaker, L is the total load requirement and G is the generator, DG is the diesel generator, TG is the steam turbine generator and SG is the shaft generator. These generators are conventional on-board power supply.

DG would be the primary power source on most ships; however, with the ship being fed by fossil fuel, a ship owner might also select energy recovery using TG and SG, among others, for improved power supply efficiency. The composition of the proposed PTG system within a dashed line is shown in fig. 1, that is, a method to improve the energy efficiency of the marine power. In existing ships with the diesel plant, the exhaust gas collected at the manifold is routed through the turbocharger and then released into the atmosphere via the exhaust gas economizer and a funnel.

The turbocharger drives a compressor by converting the energy obtained from the exhaust gas, and directs compressed air into the cylinders of the main diesel engine. In the system using a power turbine, part of the exhaust gas at the manifold is extracted to drive a power turbine, and the energy recovered thereby is converted to electrical power by a generator in this new power supply arrangement.

## 2.2 PTG System

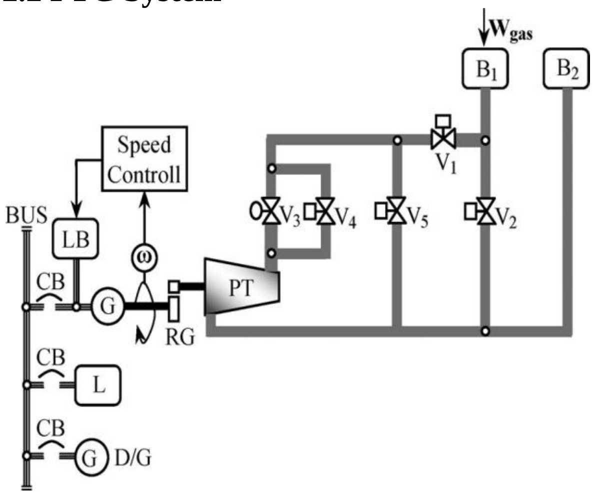

**Fig. 2. Diagram of the PTG model**

Fig. 2 shows the plant model for the PTG system. $B_1$ and $B_2$ are the boundary elements in this simulation. $B_1$, as the power source, is the exhaust-gas manifold of the main diesel engine from the main-diesel-engine cylinders. $B_2$ is the exhaust-gas element in this system.

$V_1$ through $V_5$ are valves. $V_1$ is a shut-off valve. $V_2$ is a bypass valve for the PTG system. $V_3$ is an inlet valve for gas supply to the power turbine. $V_4$ is a start-up valve for the start-up. $V_5$ is a bypass valve for the power turbine. The bypass valve $V_2$ is required to maintain the amount of gas extracted from the main diesel engine as a power-source constant [4]. PT is the power turbine, RG is the reduction gear, and LB is a load bank as a controller. BUS is the electrical system bus, with a frequency of 60 Hz and a voltage of 450V in the simulation.

When the power turbine is in the in-service state, the exhaust gas flow is supplied from $B_1$ to PT via $V_1$ and $V_3$. PT is driven by the exhaust-gas energy with a gas temperature of 415 °C at the rated speed of the main engine output. PT speed reaches approximately 20 000 r/min. G is driven by PT, but the rated speed of the generator is 1800 r/min at 60 Hz. The differential speed is high enough for the system to require a reduction gear.

## 2.3 Speed Model

The reduction-gear model is the model of the speed connecting the power turbine and the generator. The speed of the power turbine is approximately 20 000 r/min, while that of the generator is 1800 r/min. This difference is not inconsequential. When the element is considered as a rigid body, the reduction-gear model is given by (1), where $\omega$ is the angular velocity of the generator that is approximately 188.5 rad/s at rated speed and ΔT is the torque between the power turbine and the generator. J is the inertia of the PTG, and F is a friction loss.

$$J\frac{d}{dt}\omega + F\omega = \Delta T \qquad (1)$$

The PTG speed model is given by (2) according to (1)

$$J\frac{d^2}{dt^2}y + F\frac{d}{dt}y = u \qquad (2)$$

where

$$\frac{d}{dt}y = \omega \quad \mathrm{u} = \Delta\mathrm{T} \tag{3}$$

The PTG speed model of (2) transfers to the following state space model:

$$\frac{d}{dt}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \psi_1 \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \psi_2 \end{bmatrix} u(t) \tag{4}$$

$$y(\mathrm{t}) = [0 \quad 1]\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \tag{5}$$

where

$$x_1(t) = y(t) x_2(t) = \frac{d}{dt}\mathrm{y(t)} = \frac{d}{dt}x_1(t) \tag{6}$$

$$\psi_1 = -\frac{F}{J}\psi_2 = -\frac{1}{J} \tag{7}$$

The state-space model of (4) and (5) has two unknown parameters $\psi_1$ and $\psi_2$. The prediction-error method is used to estimate the unknown parameters $\psi_1$ and $\psi_2$ using (8)–(10). The estimation result is $\psi_1 = -0.039723$ and $\psi_2 = 0.075861$. The inertia J and the friction loss F of the PTG speed model are obtained by $\psi_1$ and $\psi_2$, i.e., J = 3.181848 and F = 0.523629 according to equation (7).

## 3. PROPOSED FUZZY BASED MODEL REFERENCE ADAPTIVE CONTROLLER

Fuzzy logic controller has proven effective for complex and non linear processes. Especially, when the classical control methods cannot satisfy the desired performance, the fuzzy control techniques can be considered to be a reasonable alternative. It converts a linguistic control strategy into automatic control strategy [9].

FLC consists of three components namely fuzzification, inference (knowledge base and decision making) and defuzzification. In general a fuzzy set is used to express a fuzzy variable which is defined by a membership function. The values of membership function vary between 0 and 1.

### 3.1 Membership Functions

The inputs to the Fuzzy are speed error (e) and derivative of speed error (ce). Linguistic variables of FLC for three-phase VSI include "error", "change in error" and "output" which are represented by (e), (ce) and ($U_c$) respectively. These linguistic variables take on the following values: positive big (PB), positivemid (PM), positive small (PS), zero (Z), negative small (NS), negativemid (NM), negative big (NB). The controller output is $U_c$ [8].

Triangular membership functions are chosen for inputs and outputs because of its simplicity. The decision-making process is associated with a set of fuzzy logic rules. In accordance with the linguistic rules and the linguistic values of the inputs for the fuzzifier, the linguistic value of the output is computed. We use Mamdani inference strategy. The crisp control output is obtained through centroid defuzzification [10].

### 3.2 Fuzzy Rule

The fuzzy IF-THEN rules from human operators provide good control strategies, and then the adaptation will converge quickly.

| e<br>ce | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | NB | NB | NB | NB | NM | NS | Z |
| NM | NB | NB | NB | NM | NS | Z | PS |
| NS | NB | NB | NM | NS | Z | PS | PM |
| Z | NB | NM | NS | Z | PS | PM | PB |
| PS | NM | NS | Z | PS | PM | PB | PB |
| PM | NS | Z | PS | PM | PB | PB | PB |
| PB | Z | PS | PM | PB | PB | PB | PB |

**Table 1. The Linguistic Rule Base Table**

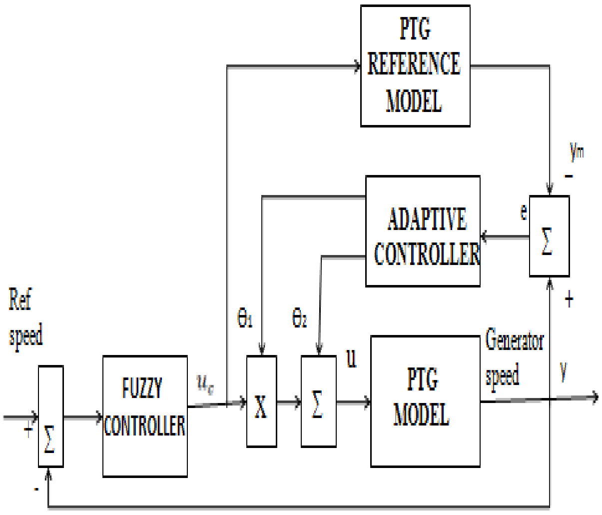

**Fig. 3 Block diagram of the Fuzzy based MRAC**

Fig. 3 shows a block diagram of a plant and a controller using the PTG system with the fuzzy based model reference adaptive controller. $\theta_1$ and $\theta_2$ are compensation parameters, *Ref is* a setting value, $u_c$ is an output of the Fuzzy controller for the input of the reference, *u* is an input of the plant, *y* is an output of model, and $y_m$ is an output of the reference model.

Equation (11) is an error between $y$ and $y_m$. The error of *e* is used for the adaptive controller of *A*. The adaptive controller estimates the compensation parameter. The rule of adaptive controller is defined by,

$$\mathrm{e} = y - y_{\mathrm{m}} \tag{11}$$

$$\frac{d\theta}{dt} = -Re\frac{\partial e}{\partial \theta} \tag{12}$$

where $\theta$ is a controller parameter, $\partial e/\partial\theta$ is a derivative of an error between the output of the plant and the output of the reference model [7], and the parameter $R$ determines the adaptation rate. Here, a speed of PTG in the plant is given by equation (13), where $u$ is the control variable and $y$ is the measured output of the plant as the speed of PTG

$$\frac{d}{dt}y = -ay + bu \qquad (13)$$

Assume that the reference model obtained a close-loop system described by

$$\frac{d}{dt}y_m = -a_m y_m + b_m u_c \qquad (14)$$

Let the controller be given by

$$u\,(t) = \theta_1\, u_c\,(t) - \theta_2\, y\,(t) \qquad (15)$$

Simulation is employed to compare MRAC with the fuzzy based MRAController.

## 4. SIMULATION RESULTS

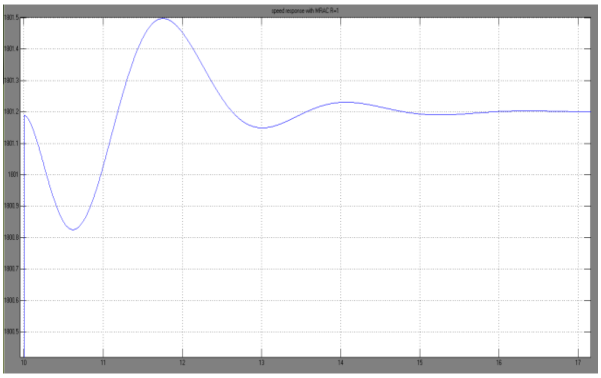

**Fig. 4 Model Reference Adaptive controller Output R=1**

Fig. 4 shows the simulation result using the model reference adaptive controller. From the Simulation result it is well understood that the speed response has overshoot. So, this overshoot should be rectified. To rectify this, Fuzzy Controller based controller added with Model Reference Adaptive controller.

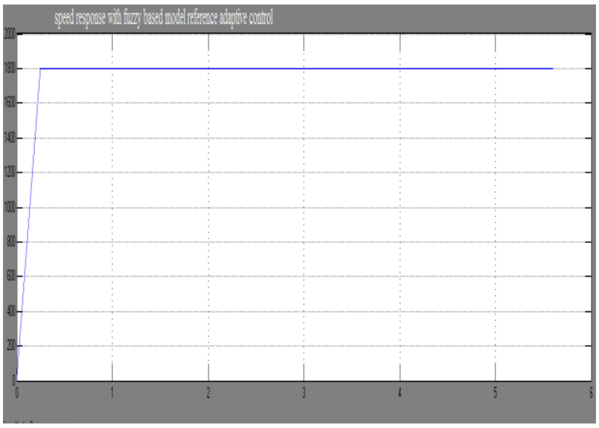

**Fig. 5 Fuzzy based Model Reference Adaptive controller Output**

Fig. 5 shows the simulation result using the fuzzy based model reference adaptive controller. From the Simulation result it is well understood that the speed response has no overshoot. The output is obtained without overshoot.

## 5. CONCLUSION

An improved fuzzy based model reference adaptive controller for the PTG system on a shipboard grid system has been presented in this paper. Simulation has been employed to evaluate by comparing the conventional controller with the proposed fuzzy based Model Reference Adaptive controller. The intelligent fuzzy logic based model based controller respond quickly without any overshoot and undershoot, and it has no steady state error. The speed response is achieved. Overshoot that appears in the base paper is being rectified in this paper using Fuzzy based Model Reference Adaptive Controller.

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