

Hybrid Control of Interconnected Diesel-generators for Marine Power Station

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Abstract—The conventional control strategy of speed regulator in marine power paralleling system is respective control for interconnected diesel-generators. Taking into account the influence of the ship power paralleling system, a hybrid control model is presented in this paper. It is proved that both speed control and power regulation of the individual diesel-generator becomes possible. To this end, a novel control strategy is developed for the design of suitable model free adaptive (MFA) controller. Using the proposed model and the new control strategy, the application of speed-power coupled control and its effectiveness are extensively studied. The method is tested on COSCO (China Ocean Shipping (Group) Company) ship power system, which is mostly used as a teaching and training system for marine electrical engineers.

Keywords- Marine power station, Speed-power regulation, Hybrid control, MFA

I. INTRODUCTION

Electrical power systems play an important role in ocean-going ships. This system usually consists of many diesel-generators and many kinds of loads while their total power demands vary continuously throughout the ship. As we all know, the ship power capacity of an individual diesel-generator is relatively low, two or more diesel-generators are necessary to run in parallel. The actual power output required from each of the interconnected diesel-generator in accordance with load changes is dealt with by speed regulators in order to keep system frequency at the scheduled value, and maintain appropriated power contributions of each interconnected diesel-generators.

The speed-power control of an interconnected power system is important in electrical power system design and operation, it is indispensable for keeping the power system frequency and interchange of power output at the specified values. Based on this idea, many control strategies have been proposed [1,2]. The marine diesel-generator's speed-frequency control system based on sliding mode control (SMC) scheme is introduced in [3], which consists of a conventional governor based on a standard speed error signal and an auxiliary loop incorporating current signal as a feedforward control. [4] presents hybrid controller (HC) combining with Siemens-Schottel-Propulsion (SSP) speed, torque and power. [5] and [6] analyze the dynamic characteristics of the diesel engine speed regulation system, build a nonlinear mathematical model and design a nonlinear H-two/H-infinity controller.

In order to meet the new control requirements, new control techniques are used in the system successfully. This paper presents a novel methodology for the design of coupling control for interconnected diesel-generators. MFA (model free adaptive) has been already applied on marine power system [7], it is capable of providing good and consistent power control performance, despite wide variations in the system operating conditions. The application of speed-power coupled control and its effectiveness is tested on COSCO (China Ocean Shipping (Group) Company) ship power system.

II. DESIGN OF HYBRID CONTROL SYSTEM FOR DIESEL-GENERATOR

In order to develop the model relevant for hybrid control strategies under the conditions discussed previously, principle diagram of interconnected diesel-generators system is shown in Fig.1, it consists of diesel engines, synchronous generators, MFA controller, fuel actuators, air control breakers (ACB) and common bus bar.

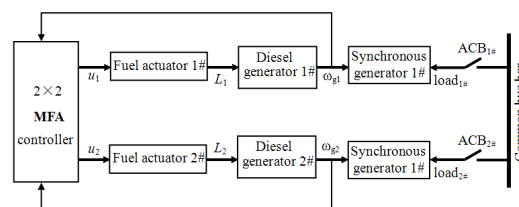


Figure 1. Principle diagram of interconnected diesel-generators

Fuel actuator proportionally converts the governor output control signals into the shaft displacement outputs. Diesel engine torque-speed characteristic is a family of smooth curves, which can be used to approximate a number of linear segments [5, 6]. Assume that all individual diesel-generator power outputs are equivalent, the governor outputs control signal in accordance with the speed-droop characteristics of each engine. The diesel engine speed determines the frequency of the ship electrical output while the diesel engine power determined by the ship electrical power load.

III. CONTROL MODEL OF DIESEL-GENERATOR

Marine synchronous generators used to convert mechanical power to ac electric power. This paper explores the operation of synchronous generators, when operating together with other generators. It is very important to establish marine synchronous generator model for ship

power system analysis. The synchronous generator model has been established in [8, 9], while operating alone. In order to develop marine synchronous generators model for a hybrid control of interconnected diesel-generators, the synchronous generators model is shown in Figure.2

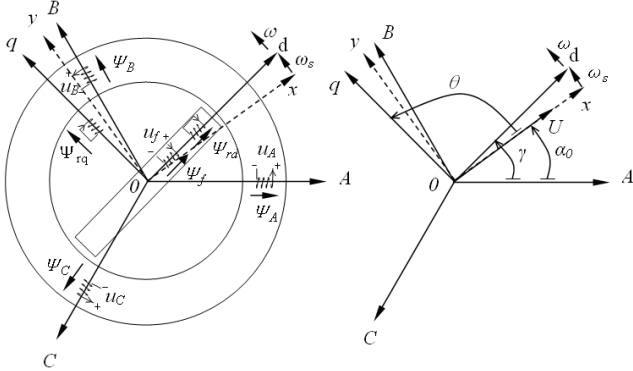


Figure 2. Structure diagrams for dual-polar generator and position of axis

Where $(\Psi_A, \Psi_B$ and $\Psi_C)$ and $(i_A, i_B$ and $i_C)$ are flux linkage and phase current of stator three-phase (A, B and C) winding, respectively. x - y is the synchronous rotation axes. d -axis is the centerline of the rotor field windings, q -axis leads d -axis 90° electrical angle along rotor rotation direction. Exciting winding f is in d -axis; the equivalent damping windings r_d and r_q belong to d -axis and q -axis, respectively. ω is the angular velocity of rotor rotation, ω_s is synchronous angular velocity.

Because the ship power system is the three-phase insulation system, zero-sequence component equal to zero. The transformation equations is marine synchronous generator is as follows:

$$\left\{ \begin{array}{l} \frac{d\Psi_d}{dt} + \Psi_q \frac{d\gamma}{dt} - RI_d = U_d = -U_{sd} \\ -\frac{d\Psi_q}{dt} + \Psi_d \frac{d\gamma}{dt} - RI_q = U_q = -U_{sq} \\ \frac{d\Psi_f}{dt} + R_f I_f = U_f \\ \frac{d\Psi_{rd}}{dt} + R_{rd} I_{rd} = 0 \\ \frac{d\Psi_{rq}}{dt} + R_{rq} I_{rq} = 0 \\ J \frac{d^2\gamma}{dt^2} + \frac{3}{2} (\Psi_d I_q + \Psi_q I_d) = M_M \end{array} \right. \quad (1)$$

For convenience, this paper utilizes x_{ad} basic value system, per-unit value equations of marine synchronous generator can rewrite Eq. (1) as follows:

$$\left\{ \begin{array}{l} p\Psi_d + \Psi_q p\gamma - ri_d = u_d = -u_{sd} \\ -p\Psi_q + \Psi_d p\gamma - ri_q = u_q = -u_{sq} \\ T_{d0} p\Psi_f + i_f = T_{d0} p\Psi_f + e_{af} = u_f \\ T_{rd} p\Psi_{rd} + i_{rd} = T_{rd} p\Psi_{rd} + e_{rd} = 0 \\ T_{rq} p\Psi_{rq} + i_{rq} = T_{rq} p\Psi_{rq} + e_{rq} = 0 \\ T_J p^2 \gamma = M_M^* - M^* = M_M^* - (\Psi_d i_q + \Psi_q i_d) \end{array} \right. \quad (2)$$

After adopting per-unit value method, marine synchronous generator flux linkage equations can obtain as follows:

$$\left\{ \begin{array}{l} \Psi_d = e_{af} - x_d i_d + e_{rd} \\ \Psi_q = x_q i_q + e_{rq} \\ \Psi_f = e_{af} - \frac{x_{ad}^2}{x_f} i_d + \frac{x_{ad}}{x_f} e_{rd} \\ \Psi_{rd} = e_{rd} - \frac{x_{ad}^2}{x_{rd}} i_d + \frac{x_{ad}}{x_{rd}} e_{af} \\ \Psi_{rq} = e_{rq} + \frac{x_{aq}^2}{x_{rq}} i_q \end{array} \right. \quad (3)$$

Substituting Eq.(3) in Eq.(2), obtained as follows:

$$\left\{ \begin{array}{l} p(e_{af} - x_d i_d + e_{rd}) + (x_q i_q + e_{rq}) p\gamma - ri_d = u_d \\ (e_{af} - x_d i_d + e_{rd}) p\gamma - p(x_q i_q + e_{rq}) - ri_q = u_q \\ e_{af} + T_{d0} p(e_{af} - \frac{x_{ad}^2}{x_f} i_d + \frac{x_{ad}}{x_f} e_{rd}) = u_f \\ e_{rd} + T_{rd} p(e_{rd} - \frac{x_{ad}^2}{x_{rd}} i_d + \frac{x_{ad}}{x_{rd}} e_{af}) = 0 \\ e_{rq} + T_{rq} p(e_{rq} + \frac{x_{aq}^2}{x_{rq}} i_q) = 0 \\ T_J p^2 \gamma + [(e_{af} - x_d i_d + e_{rd}) i_q + (x_q i_q + e_{rq}) i_d] = M_M \end{array} \right. \quad (4)$$

Where i and e are the per-units of marine synchronous generator.

Damping ratios are as follows:

$$\rho_d = \frac{r}{x_d};$$

$$\rho_q = \frac{r}{x_q};$$

$$\rho_f = \frac{r_f}{x_f};$$

$$\rho_{rd} = \frac{r_{rd}}{x_{rd}};$$

$$\rho_{rq} = \frac{r_{rq}}{x_{rq}}$$

Coupling coefficients are as follows:

$$\mu_d = \frac{x_{ad}^2}{x_f x_d} = \frac{x_d - x'_d}{x_d} = 1 - \frac{x'_d}{x_d} = 1 - \sigma_d;$$

$$\mu'_d = \frac{x_{ad}^2}{x_{rd} x_d} = \frac{x_d - x''_d}{x_d};$$

$$\mu_q = \frac{x_{aq}^2}{x_{rq} x_q} = \frac{x_q - x''_q}{x_q};$$

$$\mu_a = \frac{x_{ad}^2}{x_f x_{rd}} = g_1 g_2;$$

$$g_1 = \frac{x_{ad}}{x_f} = \sqrt{\frac{\mu_d \mu_a}{\mu'_d}}; \quad g_2 = \frac{x_{ad}}{x_{rd}} = \sqrt{\frac{\mu'_d \mu_a}{\mu_d}}$$

Where μ_d , μ'_d , μ_q and μ_a are mutual inductance coefficients of stator three-phase and excitation circuit, stator three-phase and vertical axis damping circuit, stator three-phase and abscissa axis damping circuit, excitation circuit and vertical axis damping circuit, respectively. σ_d is leakage coefficient of stator three-phase and excitation circuit, x_d and x_q are the vertical and horizontal axis reactance, respectively; x'_d is the vertical axis transient reactance; x''_d and x''_q are the vertical and horizontal axis subtransient reactance, respectively.

Revolution slip is as follows:

$$s = \frac{\omega - \omega_s}{\omega_s} \quad (5)$$

Assume that vector voltage and synchronous rotation axis is coincidence, as follows:

$$\gamma = \theta - \frac{\pi}{2} + \alpha_0 + \omega_s t \quad (6)$$

From Eq.(5) and (6) one can arrive at

$$\begin{cases} s = \frac{\omega - \omega_s}{\omega_s} = \frac{d\theta}{\omega_s dt} = p\theta \\ p\gamma = \frac{d\gamma}{\omega_s} = \frac{d\theta}{\omega_s} + \omega_s = p\theta + 1 = s + 1 \end{cases} \quad (7)$$

Therefore, substituting damping ratio ρ , coupling coefficient μ and Eq.(7) in Eq.(4) we obtain

$$\begin{cases} -(\rho_d + p)x_d i_d + p(e_{af} + e_{rd}) + (1+s)x_q i_q + (1+s)e_{rq} = u_d \\ -(\rho_q + p)x_q i_q - p e_{rq} - (1+s)x_d i_d + (1+s)(e_{af} + e_{rd}) = u_q \\ -\mu_d p x_d i_d + (\rho_f + p)e_{af} + g_1 p e_{rd} = \rho_f \mu_f \\ -\mu'_d p x_d i_d + (\rho_{rd} + p)e_{rd} + g_2 p e_{af} = 0 \\ \mu_q p x_q i_q + (\rho_{rq} + p)e_{rq} = 0 \\ p\theta - s = 0 \\ T_J p s + [(e_{af} - x_d i_d + e_{rd})i_q + (x_q i_q + e_{rq})i_d] = M_M \end{cases} \quad (8)$$

$e_{rd} = e_{rq} = 0$ expresses undamped circuit condition,

Eq.(8) can be simplified as follows:

$$\begin{cases} -(\rho_d + p)x_d i_d + p e_{af} + (1+s)x_q i_q = u_d \\ -(\rho_q + p)x_q i_q - (1+s)x_d i_d + (1+s)e_{af} = u_q \\ -(x_d - x'_d) p i_d + (\rho_f + p)e_{af} = \rho_f \mu_f \\ p\theta - s = 0 \\ T_J p s + e_q i_q = M_M \end{cases} \quad (9)$$

Actuator differential equation [5] is expressed as follows:

$$\frac{dL}{dt} = -\frac{L}{T} + \frac{K}{T} u \quad (10)$$

Where L is the displacement of actuator output shaft, u is the control signal of the speed regulator; T and K are the time constant and gain of the actuator, respectively.

The dynamic equation of the diesel-generator [6] is:

$$J \frac{d\omega_g}{dt} + \xi p \omega_g = Q_1 - Q_2 \quad (11)$$

Where J , ω_g and ξ are the moment of inertia, the rotation speed and the damping coefficient of the diesel-generator, respectively. p is the generator pole pairs, Q_1 is the diesel engine output torque, Q_2 is the generator resistance torque.

Marine synchronous generator model [8] equation is as follows:

$$J \ddot{\delta} + \xi \dot{\delta} = P_1 - P_2 \quad (12)$$

Where δ is the generator rotor angle referred to the infinite bus, P_1 is the mechanical power supplied by the diesel engine, P_2 is the electrical power.

Since engine torque-speed characteristic can be used to approximate linear segments, the hybrid control model of the speed regulating system can be approximated as the convolution of linear part, integral part and first-order inertial part, its transfer function is as follows:

$$G(s) = (K_1 s + b) * \frac{1}{T_1 s} * \frac{K_2 e^{-\tau s}}{1 + T_2 s} \quad (13)$$

Where K_1 and b are the slope and intercept of the segment corresponding to the rated speed, T_1 is the integral

constant, K_2 , T_2 and τ are the gain, inertia and delay time of the hybrid control model, respectively.

MFA controller based on neural network technology including decoupling control technology is used to combine control of the individual speed regulator of each paralleling engine, to overcome adverse effects of superimposing or offsetting control action between interconnected diesel-generators.

IV. SIMULATION RESULTS

In this paper, the main parameters of diesel engine speed control system are as follows:

Diesel-generator rated power $P=50\text{kW}$, maximum power $P_{\max}=62\text{kW}$; rated speed $n=1800\text{rpm}$, diesel-generator moment of inertia $J=2.873\text{kg}\cdot\text{m}^2$, diesel-generator damping coefficient $\zeta=0.23$, generator pole pairs $p=2$, engine rated torque $Q=47.6\text{Nm}$, the maximum output shaft travel of fuel actuator $L_{\max}=8\text{mm}$.

The parameters of the hybrid control model are as follows:

$K_{11}=1$, $K_{12}=1$; $K_{21}=1$, $K_{22}=1$; $T_{11}=1.5\text{s}$, $T_{12}=1.5\text{s}$; $T_{21}=3\text{s}$, $T_{22}=5\text{s}$; $\tau_1=3\text{s}$, $\tau_2=5\text{s}$; $b_1=0.6$, $b_2=0.65$; sample interval $T_s=0.1\text{s}$. K_{1i} , K_{2i} , T_{1i} , T_{2i} , τ_i and b_i are parameters corresponding to K_1 , K_2 , T_1 , T_2 , τ and b , where $i=1$ and $i=2$ represent 1# and 2# diesel-generators, respectively. The amplitude of load disturbance is 10%, white noise amplitude is 8.

The No.1# and 2# diesel-generators operate in parallel, the simulation results are as shown in Fig.3 and Fig.4. $\Delta P/P_{\max}$ and $\Delta L/L_{\max}$ are the percentage of power outputs of diesel engine and displacements of actuator output shaft, respectively.

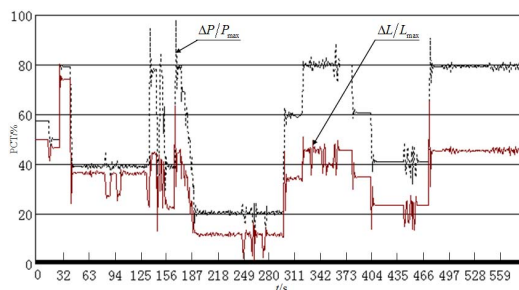


Figure 3. Simulation result of 1# diesel-generator

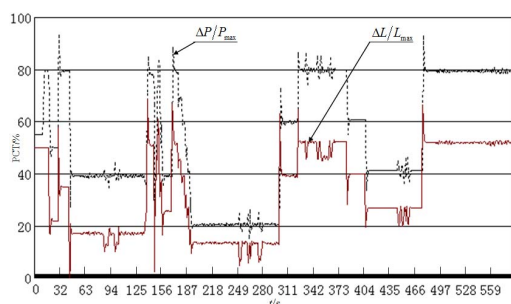


Figure 4. Simulation result of 2# diesel-generator

In Fig.3 and Fig.4, also shows the power distribution and the displacement changes of fuel oil rack between diesel-generators in parallel. Time constant and delay time of 2# are longer than that of 1#, which means $T_{22}>T_{21}$ and $\tau_2>\tau_1$. The ΔP and ΔL curves of 2# also oscillate intensely than that of 1# under transient disturbance, the 1# and 2# power distributions are equally shared in steady state, but the 1# fuel oil supply is obviously different from that of 2#, because of their different model parameters. When load disturbance or any changes of 1# and 2# power occurs, 1# and 2# output will synchronously change, so as to maintain interconnected system stability.

V. SUMMARIES

In this paper, a novel approach for the hybrid control of interconnected diesel-generators is proposed. A hybrid controller design for speed-power control of interconnected diesel-generators has been developed based on MFA technique. The performance of the hybrid controller has been verified by simulating a two interconnected diesel-generators system, to keep the frequency of the ship power system at scheduled value and to allocate the power equally to the individual diesel-generators.

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