Efficiency estimation method of synchronous generator in low power factor condition

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1. Introduction

Generally, marine diesel engine generators are assumed to be operated at around power factor of 0.8 to 1.0. However, it is often observed that onboard marine diesel generator runs at a lower power factor than 0.8. Especially for electric propulsion system in ships, it is desirable to understand how does low power factor affects on fuel consumption, as all power and electric power are supplied through generators. But in general, the generator efficiency data is available only at a power factor of 0.8 and 1.0 in shop trial data. (Table 1) Therefore, the efficiency of synchronous generators under low power factor conditions needs to be estimated by the shop trial data. In this paper, we describe the estimation methods to calculate synchronous generator's efficiency by using limited data which is provided in the shop trial data sheet.

2. Theoretical method for estimating efficiency of generator

Power loss P_{loss}[kW] on generator is determined by various faction. However, it is defined as a function of the load factor x and power factor $cos\theta$ in this paper. It can be divided into several power loss as follows.

$$P_{loss}(x, \cos\theta) = P_m + P_f + P_c + P_S + P_i \quad (1)$$

Mechanical loss P_m[kW] includes bearing friction loss and windage loss which are considered as constant and independent from electrical conditions. Power loss on field coil P_f[kW] depends on the load factor and the power factor, but its influence on the generator's efficiency is limited. Therefore, P_f [kW] can be considered as a fixed loss like the mechanical loss. The copper loss P_c[kW] and stray loss P_S[kW] of armature conductor is caused by the load current I_L[A]. Both of them are proportional to the square of I_L[A]

$$P_c + P_s = I_L{}^2(R_\omega + R_s) \cdot 10^{-3} \quad (2)$$

Table 1. Excerption of shop trial data of onboard synchronous generator

Ratings and specifications						
Voltage		450V				
Current		1203A				
Frequency		60Hz				
Phase		3				
Pole		8				
Speed		900rpm				
Efficiency						
Load factor, %		25	50	75	100	125
Power	0.8	89.7	93.1	93.7	93.5	93.0
factor	1.0	90.6	943	95.3	95.5	95.5

where, R_ω [Ω] represents the resistance of armature conductor, and R_s[Ω] represents the resistance of stray energy loss. Also the load current I_L[A] represents bellow.

$$I_L = \frac{10^3 P_{gen}}{\sqrt{3}V cos\theta} \quad (3)$$

Substituting (3) into (2), the following formula is obtained.

$$P_c + P_s = \frac{10^3 P_{gen}{}^2(R_\omega + R_s)}{3V^2 cos^2\theta}$$

$$= \frac{P_{raiting}{}^2(R_\omega + R_s)}{30V^2} \cdot \frac{x^2}{cos^2\theta} \quad (4)$$

where, $P_{raiting}$ [kW] is the rating power of the generator, and x [%] is the load factor defined as $100\,P_{gen}/P_{raiting}$.

The Iron loss P_i[kW] can be dived into hysteresis loss P_h[kW] and eddy current loss P_e[kW].

Hysteresis loss P_h[kW] depends on the maximum flux density B_m[T], frequency f[Hz], quality of steel, and size of the armature.

$$P_h = 10^{-3} k_h f B_m{}^n \quad (5)$$

where, k_h and n are empirically derived constants for a given material. n is typically in the range of 1.5 to 2.5, and a value of 1.6 is often used for estimation purpose. On the other hand, eddy current loss P_e[kW] in armature.

$$P_e = 10^{-3} k_e (t_m f B_m)^2 \quad (6)$$

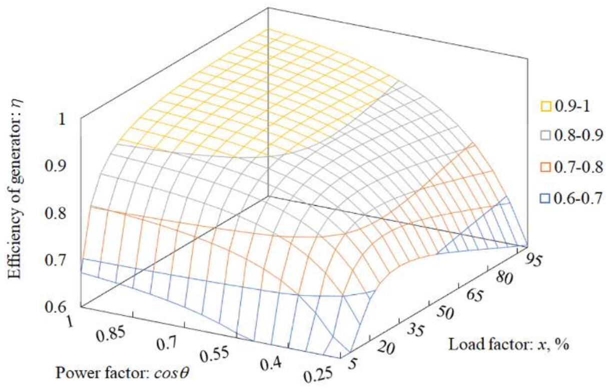

Fig 1. Efficiency map estimated by the energy dissipation mechanism of synchronous generator

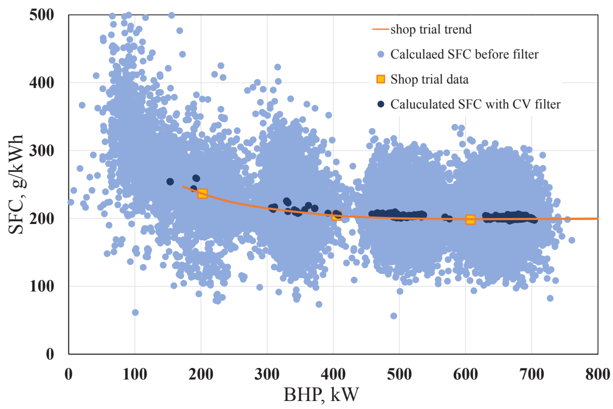

Fig 2. Shop trial data and calculated SFC data with CV value less than 0.01 for 10min.

where, k_e is an empirical a derived constant for a given material, and t_m [m] is the material thickness. Substituting these losses into (1), the following formula is obtained.

$$P_{loss}(x_g, \cos\theta) = \frac{{P_{raiting}}^2 (R_\omega + R_s)}{30V^2} \cdot \frac{x^2}{\cos^2\theta}$$
$$+10^{-3} k_h f {B_m}^n + 10^{-3} k_e (t_m f B_m)^2 + P_f + P_m \quad (7)$$

Especially, if the load factor x is a given value x_g, the function can be simplified as follows.

$$P_{loss}(x_g, \cos\theta) = a_{xg} \frac{1}{\cos^2\theta} + b_{xg} \quad (8)$$

where, a_{xg} and b_{xg} are as follows.

$$a_{xg} = \frac{{P_{raiting}}^2 (R_\omega + R_s) {x_g}^2}{30V^2}$$
$$b_{xg} = 10^{-3} k_h f {B_m}^n + 10^{-3} k_e (t_m f B_m)^2 + P_f + P_m$$

Therefore, if two coordinates are given on x and $cos\theta$ plane, the a_{xg} and b_{xg} can be calculated. Accordingly, these relationship between P_{loss} and $\cos\theta$ can be determined based on the values given in Table1. Implementing interpolation and extrapolation using these approximation formulae, estimated efficiency η was obtained (Fig 1). As is clean from the figure, the efficiency is deteriorated not only in low load factor conditions but also in low power factor conditions.

3. Validation of estimated results

To evaluate the estimated efficiency η, it is necessary to know BHP of the prime mover. However, due to the limited narrow physical space between the engine and the generator, it is difficult to measure BHP. On the other hand, SFC of diesel engine can be obtained in the shop trial data. Calculating SFC with the estimated efficiency provided in Fig. 1 and comparing it with the shop trial data, it is possible to evaluate the validity of the efficiency estimation methods. In order to validate the proposed method, SFC of the prime mover engine was calculated by using observed data including fuel oil consumption rate, oil temperature, density and output electric power of the generator. Fig. 2 shows the result of calculation. The calculated SFC varies widely compared to the shop trail data due to load fluctuations and other factors. For eliminating the variation, CV (coefficient variation) filter was applied to the observed operation data. The filter removed data that CV of generator's electric power is over 1%. Then the calculated SFCs fit well to the shop trial trend. By explicitly removing the variations from the observed data, the calculated results fit smoothly with the trends in the shop trial.

Regarding the shop trial trend as a true function, RMSE (Root Mean Square Error) of estimated SFC values can be calculated. It was calculated in a condition of low power factor of less than 0.7 for evaluating the estimated method. As a result, the estimation method showed very high precision with RMSE of 3.501[g/kWh]. It is concluded that the proposed estimation method can be utilized to estimate the generator efficiency based on the limited shop trial data.