

Parametric optimization of power system for a micro-CCHP system

Li Yinglin¹ Zhang Xiaosong²

(¹School of Power Engineering, Nanjing Normal University, Nanjing 210024, China)

(²School of Energy and Environment, Southeast University, Nanjing 210096, China)

Abstract: The universal mathematical model of an engine is established, and an economical zone, in which an engine mainly provides medium output load at medium speed, is presented. Based on the experimental data and the universal model of such an engine above, a mathematical model of a refitted engine is provided. The boundary of the corresponding economical zone is further demarcated, and the optimal operating curve and the operating point of the engine are analyzed. Then, the energy transforming models of the power system are established in the mode of cooling, heating and power (MCHP), the mode of heating and power (MHP) and the mode of electricity powering (MEP). The parameter matching of the power system is optimized according to the transmission ratios of the gear box in the power distribution system. The results show that, in the MCHP, the speed transmission ratio of the engine to the gear box (i_{es}) and the speed transmission ratio of the motor to the gear box (i_{ms}) are defined as 2.9 and 1, respectively; in the MHP, when the demand load of the power system is less than the low critical load of the economical zone, the speed transmission ratio of the motor to the engine (i_{me}) is equal to 1, and when the demand load of the power system exceeds the low critical load of the economical zone, i_{me} equals 0.85; in the MEP, the optimal value of i_{ms} is defined as 2.5.

Key words: combined cooling, heating and power; distributed energy supply; battery bank; engine

In the 21st century, harmonious development among the economy, environment and energy has become a common goal around the world. Distributed combined cooling, heating and power systems (CCHP), originated from combined heat and power systems (CHP), have an increasingly important role today. The capacity of distributed CCHP systems ranges from less than 1 kW in domestic dwellings to more than 10 MW in a community, and as much as 300 MW to supply energy in a district of a city^[1]. Ref. [2] defined “everything under 1 MW” as “small-scale”, and “mini” usage is less than 500 kW and “micro” usage is less than 20 kW. Maidment and Tozer^[3] mentioned energy management of an engine-based CCHP system with the application of an absorption chiller. Miguez et al.^[4-5] illustrated the design and the performance of a CCHP system with engine and heat pump equipment. Smith and Few^[6] also analyzed a similar CCHP system with engine and heat pump equipment. Moss et al.^[7] attempted to combine the Joule cycle with an internal combustion engine by gas turbine. Wang et al.^[8] com-

pared a small engine with an absorption chiller to generate cooling capacity.

One of the smallest CCHP applications currently in use comprises a 12 kW gas-fired reciprocating engine, a 10 kW absorption chiller, a floor radiant heating system, a waste heat recovery, a hot water tank and a cooling water tower^[8-9]. Although they are mature in technology, the small CCHP systems above have several obvious drawbacks. First, the chiller in the small CCHP system can only adopt an absorption unit or a single-effect absorption unit, and the COP of the single-effect absorption chiller is as low as 0.65 to 0.75, which damages the overall performance of the small CCHP system. Secondly, during the hot summer, the required cooling capacity of users usually exceeds the maximum output capacity of the chiller limited by recovered waste heat. To enhance the cooling capacity of the chiller, additional heating sources such as boilers are indispensable to complement the shortage of recovered heat.

To overcome the shortcomings mentioned above, this paper presents a micro-CCHP system employing a motor/generator and an additional battery bank.

1 Micro-CCHP System Based on Engine-Driven Chiller

1.1 Principle of the micro-CCHP system

As presented in Fig. 1, this micro-CCHP system employs a motor/generator and an additional battery bank. The former can be used as either a motor or a generator. And, this micro-CCHP system mainly comprises three subsystems: the power system, the heat recovery system, and the refrigeration system. The power system consists of the engine, the motor/generator, the D/C inverter, the battery bank, and the power distribution system (PDS).

1.2 Operating modes of the micro-CCHP system

The micro-CCHP system, which can synchronously supply cooling capacity and heating capacity as well as electricity, mainly works in three operating modes as follows:

1) Mode of cooling, heating and power (MCHP)

The motor/generator works as a generator. The power distributing system (PDS) drives the compressor of the refrigeration system to supply cooling capacity, and drives the generator to produce electricity simultaneously. The battery bank and the D/C inverter remain idle.

2) Mode of heating and power (MHP)

The motor/generator is also used as a generator. The output load of the engine is entirely supplied to the generator, and the alternating current produced by the generator is supplied to users under the control of the PDS.

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Biographies: Li Yinglin (1979—), male, graduate, lecturer; Zhang Xiaosong (corresponding author), male, doctor, professor, rachpe@seu.edu.cn.

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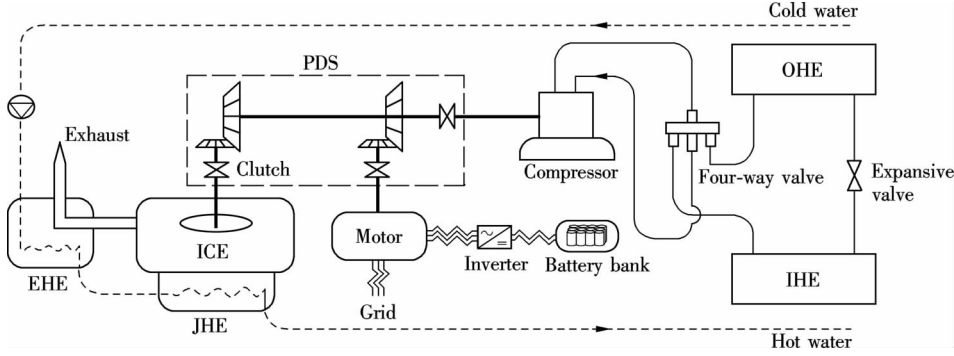


Fig. 1 Schematic of the micro-CCHP system based on engine-driven chiller

3) Mode of electricity powering (MEP)

The motor/generator, as an electromotor, drives the compressor of the refrigeration system to supply cooling capacity. If the state of charge (SOC) of the battery bank is lower than its initial discharging SOC, the battery bank will be charged by the alternating current from an electrical network.

1.3 Mathematical model and performance analysis of the engine

This study is to analyze the steady-state performance of the micro-CCHP system, so a steady-state mathematical model for an engine is established. The experimental model based on two-dimensional surface fitting is selected for the engine. The mathematical model of the universal performance map of the engine can be written as

$$\begin{bmatrix} g_{e1} \\ g_{e2} \\ \vdots \\ g_{ek} \end{bmatrix} = \begin{bmatrix} 1 & n_{e1} & T_{e1} & n_{e1}^2 & n_{e1}T_{e1} & T_{e1}^2 & \dots & n_{e1}^r & n_{e1}^{r-1}T_{e1} & \dots & T_{e1}^r \\ 1 & n_{e2} & T_{e2} & n_{e2}^2 & n_{e2}T_{e2} & T_{e2}^2 & \dots & n_{e2}^r & n_{e2}^{r-1}T_{e2} & \dots & T_{e2}^r \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & n_{ek} & T_{ek} & n_{ek}^2 & n_{ek}T_{ek} & T_{ek}^2 & \dots & n_{ek}^r & n_{ek}^{r-1}T_{ek} & \dots & T_{ek}^r \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{kk} \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_K \end{bmatrix} \quad (1)$$

where $a_i (i = 1, 2, \dots, kk)$ is the coefficient of the model; $e_i (i = 1, 2, \dots, K)$ is the random error of the model; g_{ei} , n_{ei} and $T_{ei} (i = 1, 2, \dots, K)$ are the fuel consumed ratio and the speed and the torque of the engine, respectively; r is the order of the model; K is the number of the testing data; $kk = (r+1)(r+2)/2$.

Eq. (1) can be given by $G_e = GA_m + E$, where G_e and E are a K -by-1 matrix and an EK -by-1 matrix, respectively, and G is a K -by- kk matrix. According to the extremum principle, we have

$$\begin{aligned} \hat{A}_m &= \text{inv}(G^T \times G) \times (G^T \times G_e) \\ \hat{G}_e &= G\hat{A}_m \end{aligned} \quad (2)$$

Substituting Eq. (2) into Eq. (1) gives

$$g_e = [1 \quad n_e \quad T_e \quad n_e^2 \quad n_eT_e \quad T_e^2 \quad \dots \quad n_e^r \quad n_e^{r-1}T_e \quad \dots \quad T_e^r] \begin{bmatrix} a_1 \\ a_1 \\ \vdots \\ a_{kk} \end{bmatrix} \quad (3)$$

1.4 Parameters and performance of the engine

In this study, the given engine is a four-stroke, water-cooled, in-line and inclined-installation engine refitted from a type of LJ276M motorcycle petrol engine. And the structure and the testing parameters of the refitted engine are shown in Tab. 1. The engine consumes natural gas.

Tab. 1 Parameters of ICE in power system

Item	Specification
Type	Four-strokes, water-cooled, gas-fired
Number of cylinders	2
Speed range/($r \cdot \min^{-1}$)	500 to 4 800
Compression ratio	8.4
Displacement/L	0.644
Bore, stroke/mm	76, 71
Maximum torque/($N \cdot m$)	31.9
Speed/($r \cdot \min^{-1}$)	2 900 to 3 100
Maximum output capacity/kW	12.5

For the engine in Tab. 1, according to Eq. (3), applying the mathematical model of the engine above, the mathematical model of the universal performance map of the engine can finally be written as

$$g_e = (-6.2394 + 52.1233y + 25.8x - 162.38y^2 - 63.2348xy - 52.1188x^2 + 223.9955y^3 + 93.3055xy^2 + 37.5494x^2y + 53.4947x^3 - 112.4683y^4 - 47.5775xy^3 - 24.6562x^2y^2 - 7.511x^3y - 20.7046x^4) \times 300 \quad (4)$$

where $x = n_e/5\,000$, $y = T_e/50$, $r = 4$. The relative fitting degree $\theta = 93\%$.

1.5 Definition of the economical zone of the engine

This paper defines the economical zone of the engine as an operating zone in which the thermal efficiency of the engine should be not less than 0.25. The boundary of this economical zone, in which the thermal efficiency of the engine just is equal to 0.25, consists of two parts: the economical upper bound and the economical lower bound (see Fig. 2). Also, the optimal torque curve in the economical zone makes sure that the thermal efficiency of the engine should remain optimal while running at different speeds. Similarly, the optimal operating point of the engine is defined as the operating condition in that the thermal efficiency of the engine is maximal.

Based on the definitions above, according to Eq. (4), the mathematical models of the economical upper bound, the

economical lower bound and the optimal torque curve in the economical zone of the engine can be obtained, respectively.

$$\left. \begin{aligned} T_{eH} &= -0.022x^3 - 0.9858x^2 + 14.306x - 16.511 \\ T_{eL} &= -0.00987x^3 + 1.3587x^2 - 15.979x + 65.304 \\ T_{eo} &= -0.1291x^3 + 2.4887x^2 - 15.977x + 56.159 \end{aligned} \right\} \quad (5)$$

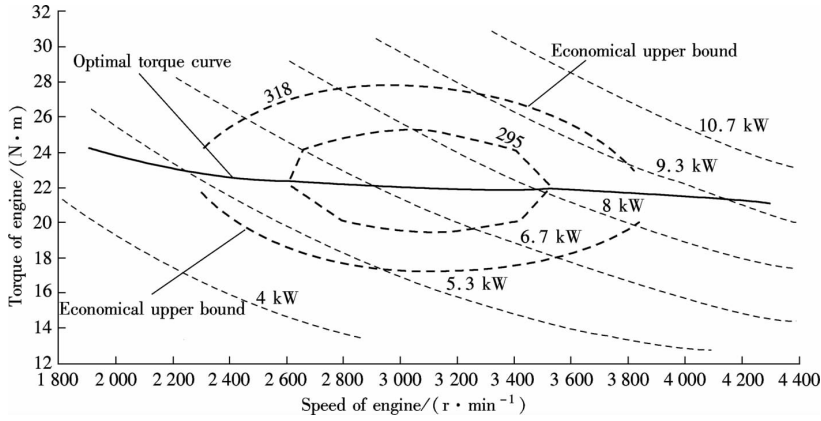


Fig. 2 Detailed boundary of economical zone of the engine

As shown in Fig. 2, the economical zone of the engine lies between the economical upper bound and the economical lower bound. In this special operating zone, the speed range of the engine is approximately 2 300 to 3 800 r/min, and the corresponding range of the output load is about 5 to 9.5 kW. Furthermore, the optimal torque curve runs through this economical zone. The speed range of the optimal torque curve is about 1 900 to 4 300 r/min, and the corresponding torque range is approximately 21 to 24 N·m. In addition, the results in Fig. 2 reveal that the optimal operating point of the engine lies in the economical zone of the engine. When the engine works at the optimal operating point, the optimal thermal efficiency of the engine can be obtained. Moreover, the optimal operating point of the engine is approximately positioned at the abscissa 3 080 r/min and the ordinate 22 N·m on the universal performance map of the engine, and the corresponding output load of the engine is about 7.1 kW.

1.6 Other components of the power system

First, considering the maximum output load of the engine P_{enM} (12.5 kW), assuming that the maximum demand load of the power system exceeds 15% of the maximum output load of the engine, the motor/generator should be used as a motor. Then the deficient load of the power system can be provided by the motor, so

$$P_{mmax} \geq \max \left\{ \frac{P_{sr} - P_{enM} \eta_{es}}{\eta_{ms} \eta_{mo}} \right\} \quad (6)$$

While the power system operates in the MHP, here, the motor/generator should be used as a generator, and the output load of the engine is entirely provided to the generator, so we obtain

$$P_{mmax} \geq P_{enM} \eta_{ms} \quad (7)$$

When operating in the MEP, the electromotor drives the compressor to chill. Assuming that the corresponding maximum demand load of the power system is equal to the maxi-

where T_{eH} and T_{eL} are the upper bound torque and the lower bound torque in the economical zone of the engine, respectively; T_{eo} is the optimal torque curve in the economical zone of the engine.

mum output load of the engine, we have

$$P_{mmax} \geq \max \left\{ \frac{P_{enM}}{\eta_{ms} \eta_{mo}} \right\} \quad (8)$$

Combining Eqs. (6) to (8), the maximum load of the motor P_{mmax} can be obtained. In this paper, the overload coefficient of the motor is defined as 1.94, and then the rated load of the motor P_{ms} can be given. Also, based on the empirical data, η_{ms} and η_{mo} are defined as 0.95 and 0.88, respectively. The main parameters of the motor utilized in the power system are shown in Tab. 2.

Tab. 2 List of other components in the power system

Component	Parameter	Value
Motor/generator (permanent magnet synchronous motor)	Rated input current/A	50
	Rated speed/(r·min ⁻¹)	3 200
	Maximum speed/(r·min ⁻¹)	8 000
	Rated input voltage/V	160
	Input voltage range/V	100 to 230
	Overload coefficient	1.94
	Rated input capacity/kW	8
	Rated torque/(N·m)	23.9
	Maximum torque/(N·m)	46.3
	Number of cells	8
Battery bank (lead-acid, cells in series, DNG12/150)	Nominal capacity/(A·h)	150
	Actual capacity/(A·h)	128
	Rated voltage per cell/V	12
	Rated current/A	50
	Rated voltage/V	96

Secondly, the total capacity of the battery bank in series is one of the most important parameters. And, the influencing factor on the total capacity of the battery bank is the operating mode of MHP. In this operating mode, when the demand load of the power system is less than the lower critical load of the economical zone, the engine runs at its optical operating point. The corresponding output load of the engine is about 7.1 kW. Part of the alternating current produced by

the generator is transported to users, and the rest is stored in the battery bank after being converted by the inverter. However, the corresponding output load of the engine (P_{eo}) is about 7.1 kW, so the maximum charging load of the battery bank (P_{bm}) is less than 7.1 kW in this operating mode. Then P_{bm} can be defined as

$$P_{bm} < P_{eo} \eta_{ms} \eta_{mo} \eta_{dc} \eta_{bc} \quad (9)$$

In this paper, the initial discharging SOC (S_c) are defined as 0.6 and 0.2. Based on the empirical data, η_{dc} and η_{bc} are defined as 0.90 and 0.92, respectively. From Eq. (9), P_{bm} is less than 4.92 kW.

In this paper, a DNG12/150 lead-acid battery is selected, and the rated voltage per cell (U_{bs}) and the rated current per cell (I_{bs}) are 12 V and 50 A, respectively. Then we obtain

$$N_m = \frac{1000P_{bm}}{U_{bs}I_{bs}}, \quad C_b \geq \frac{I_{bs}\Delta\tau_{max}}{0.6 - S_c} \quad (10)$$

where N_m is the cell number of the battery bank. Combining Eqs. (9) and (10), N_m is less than 8.2. For minimizing the initial investment and the maintenance costs of this micro-CCHP system, the capacity per cell (C_b) and the number of cells should be as small as possible. Consequently, the maximum discharging period ($\Delta\tau_{max}$) is limited to 1 h. According to Eq. (10), C_b should be no less than 125 A·h. The main parameters of the battery bank are shown in Tab. 2.

As far as other main components of the power system are concerned, there are the motor/generator, the D/C inverter and the battery bank (cells in series). The main parameters are shown in Tab. 2.

2 Energy Transform Model of the Power System

In this micro-CCHP system, the power system, which comprises the engine, the generator/motor, the D/C inverter, the battery bank and the power distribution system, can run in three operating modes: MCHP, MHP and MEP. Apparently, the power system, as the heart of the micro-CCHP system, its thermal efficiency is one significant parameter to estimate the overall energy efficiency of the micro-CCHP system. So in this section, the energy transform models of these three operating modes are further discussed.

For the MCHP, the efficiency of the power system η_{MCHP} is defined as

$$\eta_{MCHP} = \alpha \eta_e \eta_{es} + (1 - \alpha) \eta_e \eta_{ms} \eta_{mo} \quad (11)$$

$$\alpha = \frac{P_{com}}{P_{user} + P_{com}}$$

For the MHP, when the demand load of the power system is less than the low critical load of the economical zone (5 kW), the efficiency of the power system η_{MHP} is given by

$$\eta_{MHP} = \beta \eta_{emax} \eta_{ms} \eta_{mo} + (1 - \beta) \eta_{emax} \eta_{ms} \eta_{mo} \eta_{dc} \eta_{bc} \quad (12)$$

$$\beta = \frac{P_{user}}{P_{bc} + P_{user}}$$

When the demand load of the power system exceeds the low critical load of the economical zone, the efficiency of the power system η_{MHP} can be written as

$$\eta_{MHP} = \eta_e \eta_{ms} \eta_{mo} \quad (13)$$

For the MEP, the efficiency of the power system η_{MEP} can be expressed as

$$\eta_{MEP} = \gamma \eta_{net} \eta_{mo} \eta_{ms} + \eta_{net} + (1 - \gamma - \zeta) \eta_{net} \eta_{dc} \eta_{bc} \quad (14)$$

$$\gamma = \frac{P_{com}}{P_{com} + P_{bc} + P_{au}}$$

$$\zeta = \frac{P_{au}}{P_{com} + P_{bc} + P_{au}}$$

3 Power Matching of the Power System

For the gear box of the PDS, as the most important parameters, the transmission ratios of i_{es} (the speed transmission ratio of the engine to the gear box), i_{ms} (the speed transmission ratio of the motor to the gear box) and i_{me} (the speed transmission ratio of the motor to the engine) are closely related to the speed ranges of the motor, the engine and the compressor. The three transmission ratios are closely linked with the operating modes of the power system, so different operating modes of the power system should be analyzed, respectively.

For the mode of MCHP, Fig. 3 shows that while the transmission ratio i_{es} and the compressor's speed remain unchanged, the thermal efficiency of the engine decreases with the increase in the input load of the motor. With the increase in the compressor's speed, keeping i_{es} and the input load of the motor unchanged, the thermal efficiency of the engine rises to a certain peak value with a quick decrease at a higher speed.

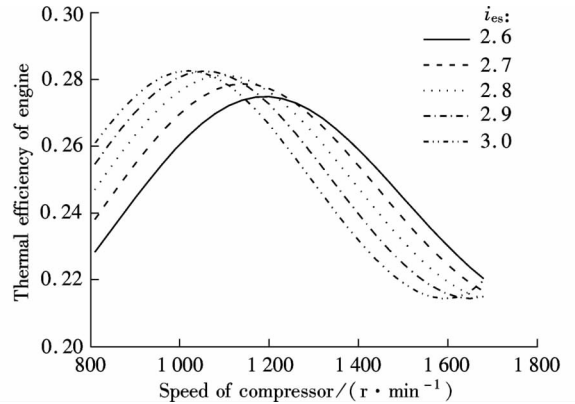


Fig. 3 The simulation curves of thermal efficiency of engine and speed of compressor with 2 kW input power load of motor

Fig. 4 indicates that the average thermal efficiency of the engine is optimized until i_{es} equals 2.9. So the optimal value of i_{es} is defined as 2.9 in the MCHP. For easy processing of the gear box, this study assumes that the speed of the motor is equal to the speed of the engine; in other words, i_{ms} is defined as 1 in the MCHP.

For the MHP, while the demand load of the power system is less than the low critical load of the economical zone, the ratio of N_{eo} to N_{ms} is 1.04. For easy processing of the gear box, here, i_{me} is defined as 1.0. When the demand load of the power system exceeds the low critical load of the economical zone, the critical maximal speed of the engine N_{ecm} is 3800 r/min in the economical zone, and the ratio of N_{ms} to N_{ecm} is 0.842. In this paper, i_{me} is limited as 0.85.

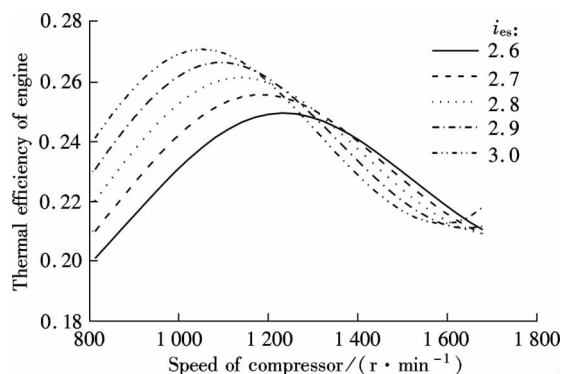


Fig. 4 Simulation curves of thermal efficiency of engine and speed of compressor with 3 kW input power load of motor

For the MEP, N_{cr} and N_{cmax} are 1 480 and 2 600 r/min, respectively. Here, i_{ms} can be limited as

$$i_{ms} \in \left(\min \left[\frac{N_{ms}}{N_{cr}}, \frac{N_{mmax}}{N_{cmax}} \right], \max \left[\frac{N_{ms}}{N_{cr}}, \frac{N_{mmax}}{N_{cmax}} \right] \right) \quad (15)$$

In this micro-CCHP system, N_{ms} is 3 200 r/min, and N_{mmax} is 8 000 r/min. After substituting them into Eq. (15), the optimal value of i_{ms} is in the range of 2.16 to 3.07, and the average of i_{ms} is equal to 2.62. Moreover, the higher the speed of the electromotor is, the lower the efficiency of the electromotor is. Furthermore, considering easy processing of the gear box, the optimal value of i_{ms} is defined as 2.5.

4 Conclusion

Based on the experimental data and the mathematical model of the given engine, the boundary of this economical zone is enclosed by an economical upper bound and an economical lower bound. In this economical zone, the speed range of the engine is approximately 2 300 to 3 800 r/min, and the corresponding output load range of the engine is about 5 to 9.5 kW. Moreover, the optimal torque curve of the engine runs through this economical zone; especially, the optimal operating point of the engine can be obtained while the engine supplies an output torque of 22 N·m at a speed of

3 080 r/min.

By analyzing the transmission ratios of the gear box, the results show that, in the MCHP, i_{es} and i_{ms} are defined as 2.9 and 1; in the MHP, when the demand load of the power system is less than the low critical load of the economical zone, $i_{me} = 1$, and when the demand load of the power system exceeds the low critical load of the economical zone, $i_{me} = 0.85$; in the MEP, the optimal value of i_{ms} is defined as 2.5.

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微型冷热电联产系统动力装置的参数优化

李应林¹ 张小松²

(¹ 南京师范大学动力工程学院, 南京 210024)

(² 东南大学能源与环境学院, 南京 210096)

摘要:建立了内燃机的通用数学模型,提出了内燃机的运行经济区.得出了改装后的 LJ276M 型内燃机的数学模型,并界定了此内燃机的运行经济区的边界范围,分析了此内燃机的运行优化曲线和最佳运行工况点.针对动力系统的冷热电、热电和供电 3 种操作模式,分别建立了能量转换数学模型,优化了动力装置的内燃机/变速箱传动比 i_{es} 、电动机/变速箱传动比 i_{ms} 和电动机/内燃机传动比 i_{me} .结果表明:在冷热电模式下, i_{es} 和 i_{ms} 的优化值分别为 2.9 和 1;在热电模式下,当动力系统需求负荷小于内燃机运行经济区的下限值时, i_{me} 取 1,而当动力系统需求负荷超过内燃机运行经济区的下限值时, i_{me} 取 0.85;在供电模式下, i_{ms} 的最优值取 2.5.

关键词:冷热电联产;分布式供能;蓄电池组;内燃机

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