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Optimal Control of Exhaust Recovery Generator System with Scroll Expander

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Abstract

A scroll expander exhaust recovery system with the battery is proposed to improve exhaust recovery efficiency. Based on the exhaust flow, storage pressure and the battery current, expander supply pressure was optimized with the loss model based on the expansion and generator loss. And then the supply pressure controller was designed to track the optimized supply pressure reference using the input-output linearization method. DC bus voltage was efficiently regulated by the PI voltage controller, the duty feedforward compensation and the operation mode of battery storage system. Experimental results proved the control strategy validity, realizing the efficiency maximum of the recovery system and exhaust discharging system.

Keywords: *Exhaust Recovery; over/deficient expansion; scroll expander; input-output linearization*

1. Introduction

Pneumatic equipment is widely used in industrial field because of the much more advantages of its security and high torque, but pneumatic system efficiency is generally low. According to the British Fluid Power Association survey, pneumatic system efficiency is only 23% to 30% [1]. A lot of energy is discharged in the form of exhaust gas. Hence, recycling the exhaust to improve the pneumatic system efficiency is much more important.

Scroll expander is a new pneumatic motor, which has compact structure, small starting torque and high efficiency of energy conversion [2]. So it is the ideal exhaust recovery devices. Literatures [3, 4] utilize scroll expander to recycle the fuel cell exhaust energy and then provide auxiliary power for the coaxial compressor, acquiring the reduction of the energy consumption of the compressor. But exhaust pressure differs greatly due to different fuel cell working condition, which makes the scroll expander always work in over/deficient expansion, so the exhaust recovery efficiency still much low. As Literature [5] described, scroll expander is used to recovery the exhaust energy discharged by the pneumatic system. By adjusting the intake air flow of the expander, storage pressure was controlled in the range of high efficient region. While the exhaust recovery efficiency is not made fully use because the gas flow control of the expander is only adopted by the on-off control, meanwhile the recovery power could not provide stable power to match the load demand. In this paper, the novel exhaust recovery system with scroll expander was proposed to elevate pneumatic system efficiency. Battery storage is adopted to decouple the load power and the exhaust recovery power. And the Scroll expander is optimized with the timely the pneumatic device working conditions.

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Accurate dynamic model is the foundation of optimal control strategy of scroll expander. The models are too complexity that not suitable for control strategies study in Literatures [6-9]. Hence, the paper firstly established average scroll expand model based on the consideration of over/deficient expansion losses. Furthermore, much more researchers focused on studying on precise position and speed track control for the pneumatic system [10-14]. This paper, Combing with constraints acquired by the exhaust gas flow, the storage pressure and the limitation of the battery charge/discharge current, the scroll expander can be optimized with the optimization function of the loss model considering the over/deficient expansion and generator copper loss.

2. Exhaust Recovery Generation System Model

2.1. Theory of Exhaust Recovery Power Generation System

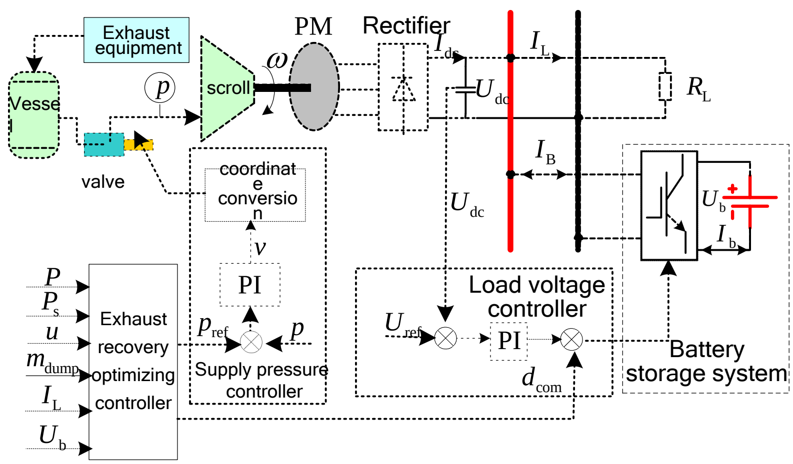

Figure 1. Sketch Map of the Exhaust Recovery System with Scroll Expander

The structure of exhaust recovery power generation system is shown in Fig.1, which includes exhaust emissions equipment, storage, scroll expander, permanent magnet generators, non-controlled rectifier, battery storage systems and valve, etc. Exhaust gas of the exhaust emissions equipment is collected to storage vessel. Due to the influence of storage pressure on the efficiency of exhaust emissions device, the three control strategies were designed to optimize the scroll expander, including exhaust recovery optimizing controller, gas supply pressure controller and load voltage controller for the efficient work of exhaust emissions device and scroll expander.

2.2. Scroll Expander Average Model

As shown in Figure 2, Scroll can be working suction, expansion and discharge etc three processions, the compressed air can be expanded in the closed chamber. In view of the variation of the supply pressure, so the scroll expander always is working in the over/deficient expansion, which seriously affects the scroll efficiency. The scroll expander torque is composed of the theoretical torque, sliding friction torque, as shown in Figure 2.

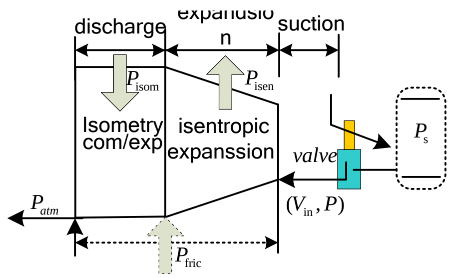

Figure 2. The Working Procession of the Scroll Expender

Compressed air can be expander in the expansion chamber, and the expansion is always working in multi-expansion between isothermal and adiabatic expansion [15]. In order to reduce the complexity of the scroll model, the isentropic expansion indicated work can be expressed as follow:

$$P_{\mathrm{Polyexp}} = \frac{\omega (P - P_{\mathrm{d}})(V_{\mathrm{s}} + V_{\mathrm{d}})}{4\pi} \tag{1}$$

Expander often runs in over/deficient expansion because the supply pressure changes. Over/deficient expansion loss can be expressed as follow:

$$P_{\mathrm{eloss}} = \frac{\omega (P_{\mathrm{i}} - P_{\mathrm{d}})(V_{\mathrm{d}} - V_{\mathrm{i}})}{4\pi} \tag{2}$$

From Eq. (1) and Eq. (2) the expander torque can be expressed as

$$M_{\mathrm{t}} = \frac{P\left[2\rho V_{\mathrm{s}} + (\rho - 1)V_{\mathrm{d}}\right] - P_{\mathrm{d}}(1 + \rho^{2})V_{\mathrm{s}}}{4\rho\pi} \tag{3}$$

Here V_{s}, V_{d} and V_{i} are the suck volume, exhaust volume and theoretical exhaust volume; ρ is fixed expansion ratio that satisfy the formula $\rho = P / P_{\mathrm{i}}$; P, P_{d} and P_{i} are the supply pressure, discharge pressure and theory discharge pressure.

The supply pressure dynamic equation of scroll expander [16] can be defined as follows:

$$\begin{cases} \dfrac{dP}{dt} = \dfrac{R T_{\mathrm{s}} \gamma (m_{\mathrm{s}} - \rho_{\mathrm{a}} q)}{V_{\mathrm{in}}} \\ q = nPV_{\mathrm{s}} + k_{1}(P - P_{\mathrm{d}}) \\ m_{\mathrm{s}} = \dfrac{c_{\mathrm{f}} S u P_{\mathrm{s}} f(P)}{\sqrt{T_{\mathrm{s}}}} \end{cases} \tag{4}$$

The function $f(p)$ is defined as

$$f(P) = \begin{cases} c_{\mathrm{k}} \left\{ \left(\dfrac{P}{P_{\mathrm{s}}}\right)^{\frac{2}{\gamma}} - \left(\dfrac{P}{P_{\mathrm{s}}}\right)^{\frac{\gamma+1}{\gamma}} \right\} & c_{0} \le \dfrac{P}{P_{\mathrm{s}}} < 1 \\ 1 & \dfrac{p_{\mathrm{a}}}{P_{\mathrm{s}}} < \dfrac{P}{P_{\mathrm{s}}} < c_{0} \end{cases}$$

where: the P_{s} is the storage pressure; R is the gas constant; c_{f} is the exhaust coefficient; c_{k} and c_{0} are respectively 3.864 and 0.528; S is the cross-sectional area of the valve; u is the valve control input; T_{s} is the storage temperature; p_{a} is the atmospheric pressure; ρ_{a} is a standard of atmospheric density; q is an inlet volume flow; m_s is an inlet mass flow; n is the rotational speed; k_1 is the leakage coefficient; V_{in} is the volume of the valve to the air intake.

2.3. Model of Permanent Magnet Generator with the Battery Storage System

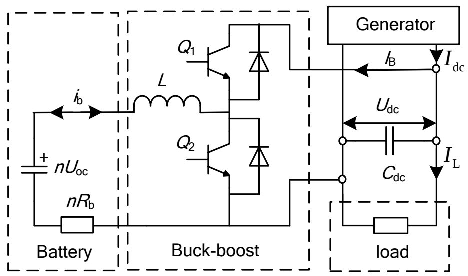

Figure 3. Circuits Structure of the Generator System

The generator uses the Buck-boost converter for battery charge and discharge through the non-controlled rectifier. There are two modes that is Buck step-down charging and Boost pressure discharge, through which DC bus voltage can be constant. Circuits Struct of the Generator System is shown in Figure 3.

The Magneto motive force and electromagnetic torque of the generator can be represented as respectively

$$E = k_e \omega \tag{5}$$

$$T_g = k_g i_s \tag{6}$$

Where ω is the angular velocity of generator; i_s is the phase current; k_e and k_g are the magneto motive force and torque coefficient respectively.

The generator phase current can be expressed as

$$L_s \frac{di_s}{dt} = E - R_s i_s - \frac{\pi U_{dc}}{3\sqrt{3}} \tag{7}$$

Here U_{dc} is DC bus voltage; L_s and R_s are winding reactance and resistance of the generator.

Dynamic equation of DC bus can be expressed as

$$\frac{1}{2} C_{dc} \frac{dU_{dc}^2}{dt} = U_{dc}(I_{dc} - I_B - I_L) \tag{8}$$

Where C_{dc} is the filtering capacitor; I_{dc}、I_B and I_L are rectifier output current of the generators, high side battery current and load current.

When $I_{dc} - I_L > 0$, the system working in the Buck mode. In this mode, the battery is charged and Q_2 is shut off, while the bus voltage can be constant due to the control of Q_1 duty ratio. when $I_B \le 0$, the system working in the Boost mode. In this mode, the battery is discharged and Q_1 is shut off, while the bus voltage can be constant due to the Control of Q_2 duty ratio.

The battery model [17, 18] can be expressed as:

$$u_b = u_{oc} - i_b R_b \tag{9}$$

Where i_b is the charge and discharge current of battery; u_b and u_{oc} are the port voltage and open circuit voltage; R_b is the internal resistance.

In view of the Buck-Boost converter dynamic response is much faster than a pneumatic system, the bus voltage is considered to be in a steady state. So the Eq. (8) can be expressed as

$$I_{dc} - I_B - I_L = 0 \tag{10}$$

Ignoring Buck-Boost converter power loss, i_b can be defined as follows:

$$i_b = \frac{U_{dc} I_B}{u_b} \tag{11}$$

In order to prevent overcharge and depth of discharge effect on battery life, the battery port voltage and current must be restricted which can be defined as follows:

$$\begin{cases} u_{oc} \in [U_{min}, U_{max}] \\ i_{bc} \le 0.1 C_b \end{cases} \tag{12}$$

Where: U_{max} and U_{min} are the battery port voltage limit user manual provided; C_b is the battery capacity; i_{bc} is the charging current.

2.4. Dynamic Model of Exhaust Recovery Power Generation System

From Eq. (3), (4), (6) and (7), it is easy to get the dynamic model of exhaust recovery power system:

$$\begin{cases} \frac{d\omega}{dt} = \frac{M_t}{J} - \frac{b_0}{J}\omega - \frac{k_g}{J} i_s \\ \frac{di_s}{dt} = \frac{k_e}{L_s}\omega - \frac{R_s}{L_s} i_s - \frac{\pi U_{dc}}{3\sqrt{3} L_s} \\ \frac{dP}{dt} = \frac{R\sqrt{T_s}\gamma C_f S u P_s f(P) - \rho_a R T_s \left(9.6\omega P V_s + k_1 (P - P_d)\right)}{V_{in}} \end{cases} \tag{13}$$

In the expression, b_0 refers to the friction damping coefficient; J refers to total moment of inertia.

2.5. Air Storage Model

With the storage (volume Vs) as the control body, the dynamic model of the storage pressure can be represented as:

$$\frac{dP_s}{dt} = \frac{\kappa R T}{V_s}(m_{dump} - m_s) \tag{14}$$

In the expression, m_{dump} refers to mass flow of exhaust emissions.

3. Control Strategy of Exhaust Recovery Power Generation System

3.1. Optimization Controller of Exhaust Recovery

In view of the influence on exhaust emissions equipment operation efficiency by storage pressure, the storage pressure must be maintained in the range ([P_{min}, P_{max}]) when the emissions equipment runs efficiently for the efficient operation of emissions equipment and scroll expander.

To improving the energy conversion efficiency of the scroll expander is reduce the loss of exhaust recovery system. System loss includes pneumatic loss and generator loss. The loss model is expressed as

$$P_{loss} = P_{eloss} + P_{cu} + P_{Fe} \tag{15}$$

In the expression

$$\begin{cases} P_{cu} = 3 i_s^2 R_s \\ P_{Fe} \approx E^2 / R_{fe} = (k_e \omega)^2 / R_{fe} \end{cases}$$

Due to battery voltage is controlled, P_{Fe} is substantially constant and relatively small, which will not be considered. According to Eq.(2) and (13), we can get the system optimization function.

$$\min_{i_{sopt}} \mathrm{P}_{loss} = a i_s^2 + b i_s + c \tag{16}$$

The initial conditions are defined as:

$$i_s \le \frac{\sqrt{6}}{\pi}\left(\frac{U_b i_{bc}}{U_{dc}} + I_L\right) \qquad U_{min} \le U_b \le U_{max}$$

In the expression,

$$a = 3R_s + \frac{4\pi R_s\left(k_g k_e + b_0 R_s\right)(V_d - \rho V_s)}{k_e^2\left[2\rho V_s + (\rho - 1)V_d\right]};$$

$$b = \frac{4\sqrt{3}\pi^2 b_0 U_{dc}\left(1 + R_s\right)(V_d - \rho V_s)}{9k_e^2\left[2\rho V_s + (\rho - 1)V_d\right]} + \frac{4\sqrt{3}(V_d - \rho V_s)U_{dc}k_g}{9k_e} + \frac{P_d\left(1 + \rho^2\right)(V_d - \rho V_s)V_s}{k_e\rho\left[2\rho V_s + (\rho - 1)V_d\right]} - \frac{P_d R_s (V_d - \rho V_s)}{k_e}$$

$$c = \frac{4\pi^3 b_0 U_{dc}^2\left(1 + R_s\right)(V_d - \rho V_s)}{27k_e^2\left[2\rho V_s + (\rho - 1)V_d\right]} - \frac{\sqrt{3}P_d U_{dc}(V_d - \rho V_s)}{9k_e} + \frac{P_d \pi U_{dc}\left(1 + \rho^2\right)(V_d - \rho V_s)V_s}{k_e\rho\left[2\rho V_s + (\rho - 1)V_d\right]}$$

In order to improve the real-time control, optimization controller will be working when the system state changed. According to the exhaust flow and storage pressure and expander working condition and exhaust pressure range, the system can run the following four kinds of condition, and the corresponding range of gas supply pressure is given.

State 1: $\frac{dP_s}{dt} \le 0 \ and \ t_{low} > t_{min} \quad P \in [P_{min}, P_{max}]$

State 2: $\frac{dP_s}{dt} < 0 \ and \ t_{low} \le t_{min} \quad P \in [P_{min}, P_s]$

State 3: $\frac{dP_s}{dt} > 0 \ and \ t_{high} > t_{min} \quad P \in [P_{min}, P_s]$

State 4: $\frac{dP_s}{dt} \geq 0 \; and \; t_{high} \leq t_{min} \quad P \in [P_s, P_{max}]$

In the expression, the t_{high} and t_{low} are referred to the time of maximum pressure. P_{max} and P_{min} are referred the maximum and minimum pressure, which can be acquired by Eq. (14).

$$\begin{cases} t_{high} = \dfrac{(P_{max} - P_s)V_s}{\kappa RT(m_{dump} - m_s)} \\ t_{low} = \dfrac{(P_{min} - P_s)V_s}{\kappa RT(m_{dump} - m_s)} \end{cases}$$

From optimization results gas supply pressure of the expander and high side current of battery can be obtained as follows:

$$P_{ref} = \frac{4\rho\pi\left(i_{sopt}\left(\dfrac{b_0 R_s}{k_e + k_g}\right) + \dfrac{b_0 \pi U_{dc}}{3\sqrt{3}k_e}\right) + P_d(1+\rho^2)V_s}{2\rho V_s + (\rho - 1)V_d};$$

$$I_B = \frac{\pi}{\sqrt{6}} i_{sopt} - I_L;$$

The feed forward compensation of load controller is expressed as below:

When $I_B > 0$, $d_{com} = u_b / u_{ref}$;

When $I_B < 0$, $d_{com} = (u_{ref} - u_b)/u_{ref}$ 。

3.2. Gas Pressure Controller

Taking the optimized supply pressure as system output, the exhaust recovery power generation system model can be converted to:

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = P \end{cases} \tag{17}$$

In the expression:

$$f(x) = \begin{bmatrix} (M_t - b_0\omega - k_g i_s)/J \\ \dfrac{k_e}{L_s}\omega - \dfrac{R_s}{L_s} i_s - \dfrac{\pi U_{dc}}{3\sqrt{3}L_s} \\ -\left(\rho_a R T_s \left(9.6\omega P V_s + k_1(P - P_d)\right)\right)/V_{in} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} 0 \\ 0 \\ R\sqrt{T_s}\gamma C_f S P_s f(P)/V_{in} \end{bmatrix}$$

Input/output feedback linearization method is used for Eq. (17).

$$\dot{y} = L_f y + L_g y u = A(t) + E(t)u \tag{18}$$

Where $L_f y$ and $L_g y$ are Lie derivative of y along the direction of f(x) and g(x) respectively.

$A(t) = -\rho_a R T_s \left(9.6\omega_g P V_s + k_1(P - P_d)\right)/V_{in}$;

$E(t) = R\sqrt{T_s}\gamma C_f S P_s f(P)/V_{in}$.

Considered v as a new control variable, the linear system is $\dot{y} = v$.

In order to achieve the fast track of gas supply pressure, the new control law can be designed.

$$v = \dot{e} + k_p e + k_i \int e\,dt \tag{19}$$

Where $e=P-P_{ref}$; k_P and k_i are proportional and integral parameters respectively.

We can get the transformation equation for turning the control variable v into u coordinates.

$$u = \frac{v - A(t)}{E(t)} \tag{20}$$

3.2. Load Voltage Controller

In order to improve the constant power supply for load voltage, we adopted the combination of PI control and feed-forward compensation controller for the constant load voltage. Load voltage controller can be represented as follows:

$$d = k_a e + k_b \int e\,dt + d_{com} \tag{21}$$

Where k_a and k_b are proportional and integral parameters of controller; d_{com} is feed-forward compensation value.

4. Performance Validations

We built a test platform for exhaust recycling to verifying the optimizing control strategy. The compressor is used to simulate the exhaust emission equipment, and the permanent magnet generator is driven by the scroll expander, while the battery storage system is designed to decouple the recycling power and the load power including the Buck-boost converter and the lead-acid battery. The discharge pressure of the emission device is defined as the range [0.45MPa, 0.5MPa], which can make the emission device be efficiently working.

Due to the variation of the working condition of the exhaust emission equipment, the supply pressure is optimized to make the storage pressure change in the efficient working pressure range as shown in Figure 4 (a). Optimization controller optimizes the generator output current as shown in Figure 6, based on storage pressure changes and exhaust flow (Figure 5). So the supply pressure of the scroll expander can be optimized by the 0.45Mpa and the intake flow is 195L/min. Storage pressure is dropped while the system status is not changed. At the time of 80s, when the storage pressure down to 0.47 Mpa, Optimization controller is activated to optimize again due to the condition of the time $t_{low}<t_{min}$. Then the optimized supply pressures are respectively set by 0.4 Mpa, 0.37 Mpa and 0.35 Mpa. Up to the 175s, scroll expander stops working because the storage pressure has been dropt to 0.45 Mpa.

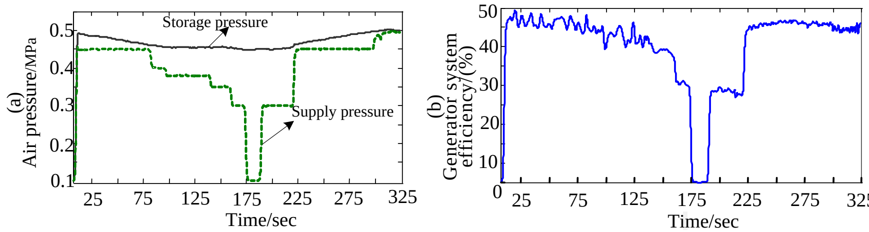

Figure 4. Variation of Air Pressure and Generator System Efficiency

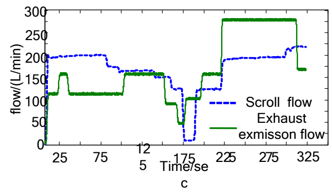

Figure 5. Variation of the Exhaust Flow and the Scroll Intake Flow

In order to prevent starting work frequently of the scroll expander, this project set the starting conditions as 0.4MPa. At the time of 188s and when the storage pressure is 0.4 Mpa, expander working with the 0.3MPa gas supply pressure. Until $t_{low}>t_{min}$, storage pressure continues to rebound, and the system supply pressure optimized is 0.45MPa due to the condition of $t_{low}<t_{min}$. Up to 300s, when $t_{high}<t_{min}$, optimization controller is restarted. At this time the gas supply pressure is 0.48 Mpa for the effective control of storage pressure and the efficient operation of the exhaust emission equipment.

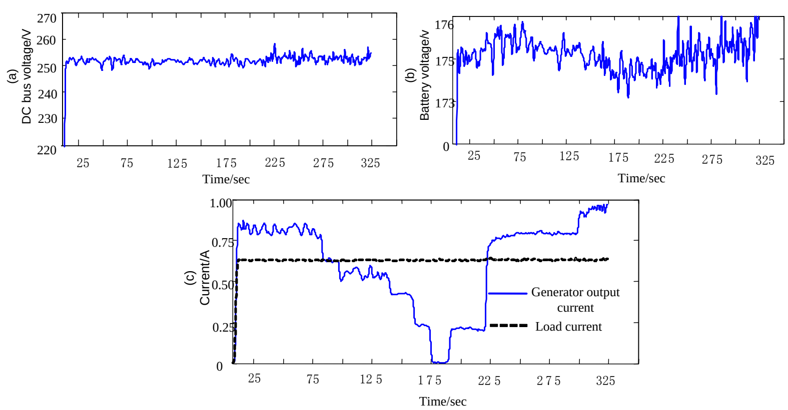

Figure 6. Variation of the DC Bus Voltage, Battery Voltage and the Current

Figure 4 (b) gives the change of power generation systems efficiency during the optimization process of exhaust recovery system. Due to the reduction of gas supply pressure, system efficiency reduces gradually from 42% to 25%. When the time is 225s, it returns to 41.5%. After the 300s, efficiency drops to about 40.5% because of the increase of gas pressure, improving the exhaust recovery system efficiency effectively. The gas pressure regulation process is shown in Figure 4 (a), achieving the quickly without static error tracking for the supply pressure optimized. Then the tracking performance of pressure tracking controller can be proved.

As shown in Figure 6 (a), with the change of working conditions of exhaust emission equipment, the DC bus voltage keeps constant so as to meet the demand of load power supply. Battery storage system mode can be given in real time, and the duty feed-forward compensation of converter can be obtained. According to Figure 6(b), in the 80 s before battery storage system is running in the Buck mode, when the generator output current and the load current are 0.8 A s and 0.625 A respectively. For the battery stores excess current, so its voltage rises. In the time from 80 s to 225 s, the system is running in the Boost mode, when the output current of the power generation system is lower than the load current (Figure 6(c)). Insufficient load power part is complemented by battery, so the battery voltage is reduced. But in the 225 s after, the system re-run in the Buck mode due to the rises of the gas supply pressure, when the power generation system output current is greater than the load current. The port voltage starts to rise as well.

Figure 6(c) gives the change of power generation system output current and load current. Although the generator output current have the same trend of the variation of gas pressure as shown in Figure 4(a), the load current can be remained constant 0.625A, and bus voltage can be realized constant 250v too. Combinations of the above will verify the effectiveness of the system optimization strategy and the load voltage controller.

5. Conclusion

The paper presents a novel exhaust recovery system with the battery. And then the scroll expander average model and power system dynamic model, the optimization function of exhaust recovery power generation system was constructed to optimize controlling the exhaust system. Combing with constraints acquired by exhaust flow pressure and the limitation of battery charge/discharge current, the scroll expander can be optimized for sake of the improvement of exhaust recovery efficiency. It can be judged the work mode of battery energy system in real time according to the generator output current and load current. Combing with the duty feed-forward compensation, the DC bus voltage can be kept constant. Based on the exhaust recycling test platform, the control strategy was valid. Storage pressure can be maintained in set exhaust pressure range to ensure the efficient operation of exhaust equipment. Scroll expander power system efficiency can be controlled from the 25% to 42%, which is far higher than pneumatic efficiency of the traditional impeller type motor.

Acknowledgements

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