International Journal of Control and Automation
Vol. 8, No. 9 (2015), pp. 255-264
http://dx.doi.org/10.14257/ijca.2015.8.9.25

Hybrid Excavator Power System Controller Design Based on Fuzzy Control

Xie Ya[1] and Huang Zhonghua[2,3]

[1]*School of Computer and communication, Hunan Institute of Engineering, Hunan 411104*
[2]*School of Mechanical Engineering, Hunan Institute of Engineering, Hunan 411104,*
[3]*The Cooperative Innovation Center of Wind Power Equipment and Energy Conversion, Hunan Institute of Engineering, Hunan 411104)*
[1]*csu_xieya@163.com*, [2,3]*csu707@163.com*

Abstract

Controller of hybrid excavator power system was designed with control target was to improve diesel engine fuel efficiency and decrease shaft rotate speed fluctuation. Controller input parameters were set as hydraulic pump required torque, hydraulic pump rotate speed and battery SOC. Controller output parameters were set as diesel engine output torque and motor torque. Diesel engine output torque was obtained according to its load characteristic curves. Control method of diesel engine throttle based on Fuzzy control was proposed. Power system working pattern switch rules were introduced. Simulation model of controller performance based on MATLAB was established. Controller working performance simulations in mining condition and formation condition were simulated. Simulation results show that hydraulic pump required torque is provided by diesel engine and motor in mining condition. Power system required torque is provided by motor in formation condition. Battery SOC curve is changed according to designed control rules. Diesel engine shaft rotate speed is almost constant during the whole working process. Diesel engine fuel consumption rate is constant in mining condition and is almost zero in formation condition.

Keywords: *Hybrid excavator; Power system; Controller design; Fuzzy control*

1. Introduction

Energy saving is a practical problem that excavator must to be faced. Traditional excavator energy saving technology were mainly focus on improving component performance, such as improving hydraulic system design method and improving power matching performance between power system and hydraulic system. Peng *et al* [1] had investigated local power match harmony technique about engine-pump and pump-load. The reasons of not harmonizing in power system between engine-pump and pump-load were analyzed. Power system overall match techniques were proposed and corresponding realization plan was given. Wu *et al* [2] had researched hydraulic excavator load power matching technique, with establishing hydraulic excavator pump control system mathematics model, power matching control of pump and load in the different working conditions was realized. Xiao *et al* [3] had researched hybrid power system parameter matching technique. The parameters of main components, such as engine, electric motor, generator and capacitor of power system were matched. Simulation results showed that power system working efficiency was improved significantly after parameters were matched. Wang *et al* [4] put forward a new control strategy based on hybrid technology to realize excavator global power match. Its control target was to achieve global power

ISSN: 2005-4297 IJCA

match and optimize power sources working point simultaneously. Experimental results showed that the control strategy could realize the target.

Excavator fuel consumption and emissions could be reduced to some extent with traditional energy saving method. But energy saving effect was limited. In the face of increasingly severe energy conservation and emission reduction requirements, excavator manufacturers need to find new technical solutions.

The world's first hybrid hydraulic excavator prototype was developed by Japan Komatsu company in 2004. 7 t hybrid hydraulic excavator was produced by Japan Hitachi company in 2006. In 2008, Japan Komatsu company developed 20t hybrid hydraulic excavator to Japanese market. Test results showed that Komatsu company 20t hybrid hydraulic excavator power system average fuel consumption could be reduced about 25% compared with traditional excavator, which showed hybrid excavator could save energy effectively.

Nowadays, hybrid excavator had become an important research object by world main excavator manufacturing enterprises. Hybrid excavator design involves many key technologies. Such as power system design technique, excavator boom potential energy recovery technique and power system control method. Huang et al [5] put forward excavator hybrid power system units installed power design method, and calculation equations of power system units installed power were also proposed. Lin et al [6] had systematical researched hydraulic excavator boom potential energy recovery technique. An energy recovery system that combines the advantages of an electric and hydraulic accumulator was proposed and the effects of system dynamic response were analyzed. Power system controller design technology is one of hybrid excavator key technologies. It directly affects power system working performance and energy consumption [7-9].

In this paper, hybrid excavator power system controller based on fuzzy control method was researched. Control target of the controller was to improve diesel engine fuel efficiency and decrease shaft rotate speed fluctuation. Controller structure was introduced and controller working performance was simulated.

2. Hybrid Power System Structure

Hybrid excavator power system had three kinds of typical structure, which were series, parallel and hybrid. Wang [10] thought parallel hybrid was more suitable for hybrid excavator after comparing energy saving effects of series and parallel hybrid, considering the factors of manufacturing cost, operation performance and component performance. Huang [11] thought parallel hybrid excavator had advantages in structural layout and energy consumption.

Parallel hybrid power system structure researched in this paper was shown in Fig.1. Diesel engine and motor drive hydraulic pump jointly with coaxial connection. Battery was used for electrical energy storing. Motor could work in driving state and generating state. Battery supplied power to motor when motor was in driving state. Battery was charged by motor when motor was in generating state. Diesel engine and motor working state were real-time controlled by controller according to hydraulic pump required power and battery SOC (State of Charge).

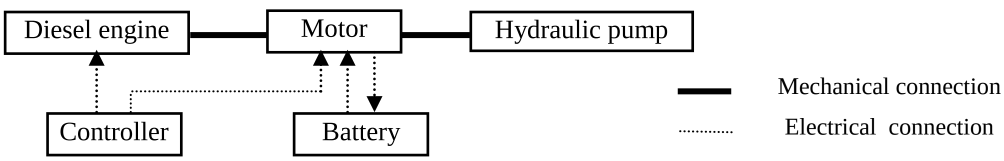

Figure 1. Parallel Hybrid Power System Structure

Parallel hybrid power system working process and working principle were as follows, diesel engine was started firstly, and diesel engine was set work in high efficiency working area secondly. Motor supplied the power difference between hydraulic pump required power and diesel engine output power in order to keep diesel engine worked in high efficiency working area. Motor was in off state or in charged state according to the difference between hydraulic pump required power and diesel engine output power when battery SOC<SOC_s (battery predefined allowed minimum SOC). Motor was work in off state or generating state according to battery SOC when hydraulic pump required power was less than diesel engine output power. Motor was work in driving state when hydraulic pump required power was great than diesel engine output power.

3. Hybrid Power System Controller Design

3.1. Controller Structure

Hybrid power system controller control target was to decrease power system shaft rotate speed fluctuation and improve diesel engine fuel efficiency. Controller structure design involves input parameters and output parameters. According to parallel hybrid power system working process and working principle, Parallel hybrid power system controller structure designed in this paper was shown in Fig.2. There were six modules in the controller, power preprocessing module, working pattern recognition module, throttle controller module, diesel engine working curve module, motor controller module and diesel engine controller module respectively. Power preprocessing module was to obtain power system average required power. Working pattern recognition module was to determine motor working state. Throttle controller module was to determine throttle opening. Diesel engine working curve module was used to determine diesel engine rotate speed and output torque according to diesel engine throttle opening. Motor controller module was used to obtain motor output torque. Diesel engine controller module was used to determine diesel engine working state.

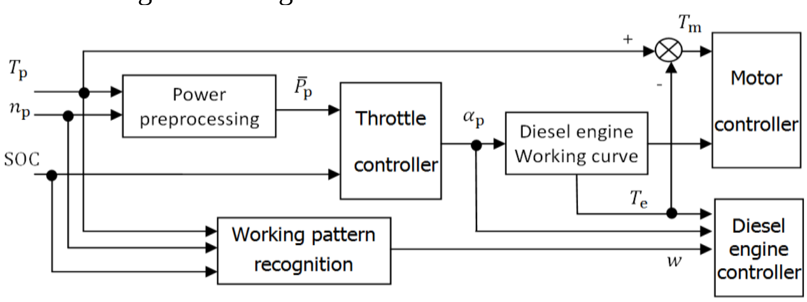

Figure 2. Hybrid Power System Controller Structure

T_p, hydraulic pump output torque; n_p, hydraulic pump output speed; SOC, battery SOC; $\bar{P}_p$, hydraulic pump average require power; α_p ,diesel engine throttle opening; T_m, motor output torque; T_e, diesel engine output torque; w, hybrid power system work pattern

Hybrid power system controller input parameters were set as hydraulic pump required torque, hydraulic pump rotate speed and battery SOC. Controller output parameters were set as diesel engine output torque and motor output torque. Diesel engine working state w was determined by working pattern recognition module according to input parameters and battery SOC. Load level was determined by diesel engine throttle controller according to the hydraulic pump required average power and battery SOC. Throttle controller output parameter was set as throttle opening. Combined with diesel engine load characteristic curves, diesel engine rotate speed and output torque could be obtained with throttle opening. Motor rotate speed was equal to diesel engine rotate speed due to motor and diesel engine were coaxial connection. Motor torque was the difference between hydraulic pump required torque and diesel engine output torque.

3.2. Power System Work Pattern

When hybrid power system was working, controller would change power system work pattern according to hydraulic pump required power, diesel engine output power and battery SOC. Combined with parallel hybrid power system working process and working principle, parallel hybrid excavator power system work patterns were defined as follows:

（1）Motor work pattern. When battery $SOC>SOC_s$ and hydraulic pump required power was low, diesel engine was in no oil injection state and motor was worked alone.

（2）Diesel engine work pattern. When hydraulic pump required power was less than diesel engine output power, motor was off and diesel engine was work alone.

（3）Motor and diesel engine jointly work pattern. When battery $SOC>SOC_s$ and hydraulic pump required power was great than diesel engine output power, motor and diesel engine were worked jointly.

（4）Charged pattern. When battery SOC was approach to SOC_s or diesel engine output power was greater than hydraulic pump required power, battery was charged by motor with diesel engine spare energy.

（5）Idle pattern. When hydraulic pump required power was zero and battery SOC was approach to SOC_s, diesel engine was in idle state.

（6）Stop pattern. When hydraulic pump required power is zero and battery $SOC>SOC_d$ (battery predefined allowed maximum SOC), diesel engine was in no oil injection state.

3.3. Diesel Engine Throttle Control Method

Diesel engine throttle control was related with power system load level and battery SOC. Considering diesel engine throttle control modeling was difficult. Fuzzy control was used as diesel engine throttle control method. Fuzzy controller with two input variables and one output variable was used. Fuzzy controller input variables were set as power system load level and battery SOC. Fuzzy controller output variable was set as diesel engine throttle opening.

Defining: P_p was hydraulic pump required power, α_e was diesel engine throttle opening. According to fuzzy controller design criterions, input and output variables membership function were defined firstly. Battery SOC was set as 0 ~ 1 according to its physical characteristics. Namely, 0 means no electricity and 1 means full power. Battery SOC normal work value was set as 0.5 ~ 0.7. Hydraulic pump required power was set as 0~35 KW according to mini excavator rated power. Mini excavator required power was 25 KW and 13 KW respectively in mining conditions and formation condition according to practical experience. Diesel engine throttle openingwas set as 0.6 ~ 1 according to practical experience. Namely, 0.6 means idle work and 1 means full open.

In this fuzzy controller, input variable and output variable fuzzy sets were set as Low, Normal and High. Input variable and output variable membership function curves were shown in Fig.3.

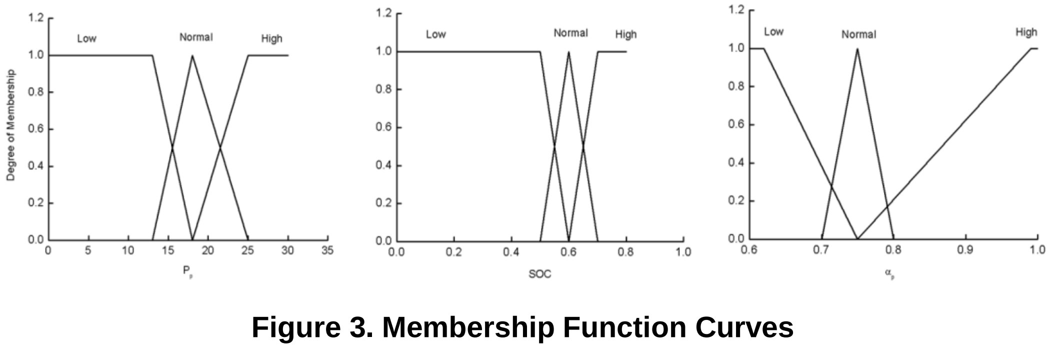

Figure 3. Membership Function Curves

Fuzzy controller control rules were determined with hybrid power system working process and working principle. Fuzzy control rules were shown in Table.1.

Table 1. Fuzzy Control Rules

α_P P_p / SOC	L	N	H
L	N	N	H
N	L	N	H
H	L	L	N

L (Low), N(Normal),H(High)

4. Controller Working Performance Simulation

4.1. Simulation Modeling

Hybrid power system controller simulation modeling was based on MATLAB software. Modular design method was used in controller performance simulation modeling. Hybrid power system controller simulation model structure was shown in Fig.4. Power preprocessing module, diesel engine throttle controller module, diesel engine working pattern recognition module, diesel engine working curve module, motor controller module and diesel engine controller module were established respectively.

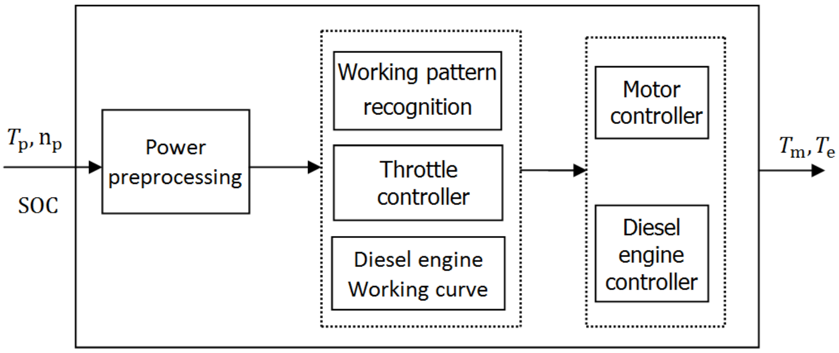

Figure 4. Controller Simulation Model

4.2. Simulation Research

Simulation conditions were as follows, mini excavator hydraulic pump input torque changing curve in mining condition and formation condition was given, and battery SOC initial value was set. Simulation results were as follows, battery SOC changing curve in the whole working process, power system components output torque changing curve in the whole working process, diesel engine throttle opening curve in the whole working process, diesel engine rotate speed curve in the whole working process, diesel engine fuel consumption curve in the whole working process.

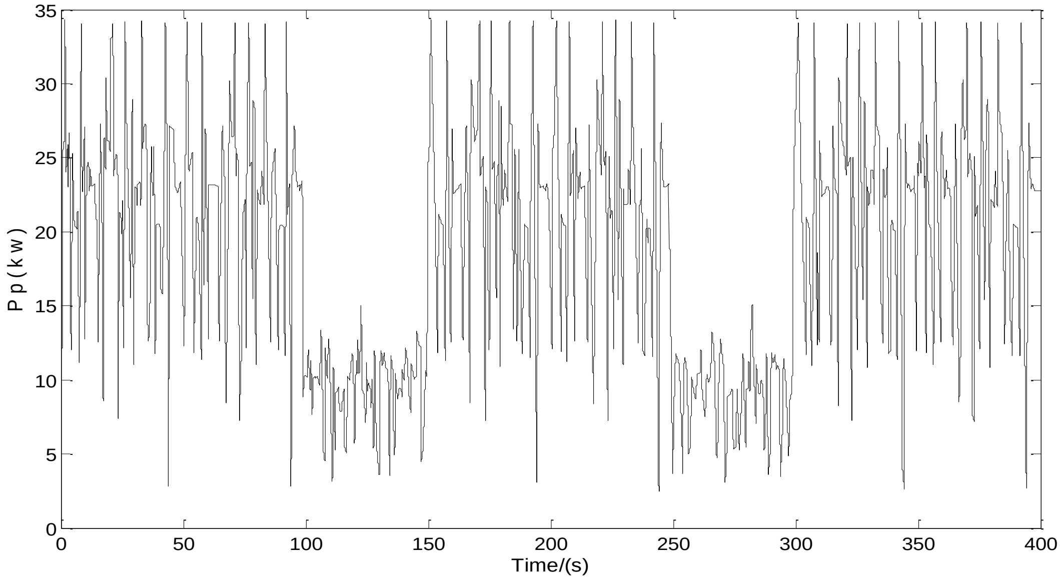

Figure 5. Hydraulic Pump Output Power Curve

5t hydraulic excavator hydraulic pump output power curve in mining condition and formation condition were shown in Figure 5. It can be seen from Figure 5 that hydraulic output power is changed dramatically. Maximum output power is almost 35 KW and minimum output power is almost 2 KW. The former 100 s is mining condition. The next 50s was formation condition. Total working time was 400s. Mining condition and formation condition were alternative. Battery SOC initial value was set as 0.6.

Excavator power system working process was simulated based on the controller simulation model. Simulation results were as follows: Hybrid power system components output torque was shown in Figure 6. Battery SOC changing curve was shown in Figure 7. Diesel engine throttle opening curve was shown in Fig.8. Diesel engine shaft rotate speed curve was shown in Figure 9. Diesel engine fuel consumption curve was shown in Figure 10.

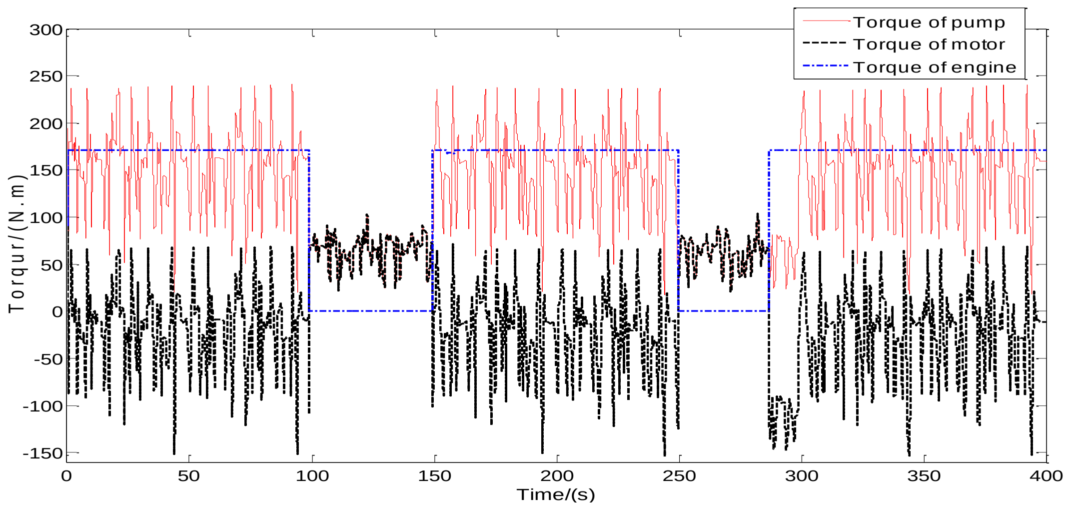

Figure 6. Component Output Torque Curve

It can be seen from Fig.6 that hydraulic pump maximum required torque is almost 240 Nm. Hydraulic pump average required torque in mining condition is almost 180 Nm. Hydraulic pump average required torque in formation condition is almost 0 Nm. Diesel engine output power is almost constant in mining condition. Diesel engine output power is almost 0 in formation condition. Motor output power is changed frequently in mining condition. In mining condition, motor output power can be plus or minus depending on the difference between pump required power and diesel engine output power. Hydraulic pump average required torque is provided by diesel engine in mining condition. Hydraulic pump average required torque is provided by motor in formation condition. In mining condition, motor is switched frequently from driving to generating to supply torque or to absorb surplus torque.

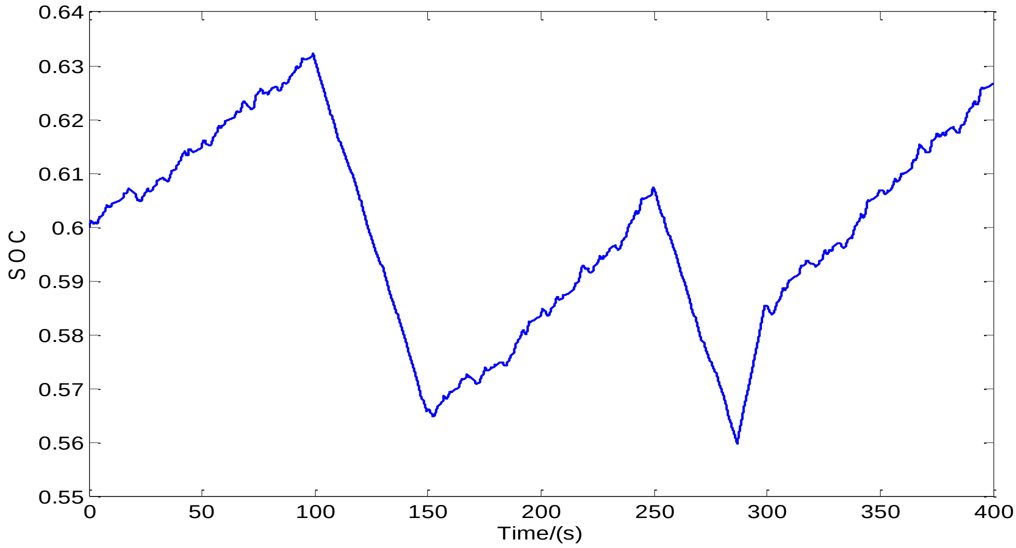

Figure 7. Battery SOC Changing Curve

It can be seen from Figure 7 that battery is charged in the former 100s although hydraulic pump required power is great than diesel engine output power. Battery SOC is decreased from 0.635 to 0.565 from 100s to 150s. In this time, excavator is in formation condition and hydraulic pump required power is provided by motor. When battery SOC is near to 0.5, battery will be charged in order to avoid battery over discharge. So, battery SOC is always in allowed working range during the whole working process.

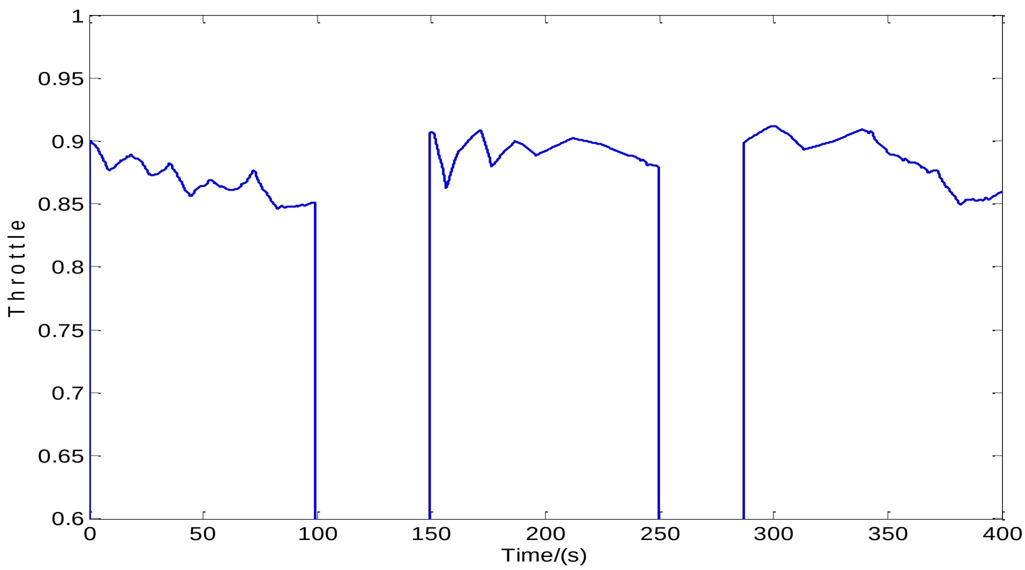

Figure 8. Diesel Engine Throttle Opening Curve

It can be seen from Figure 8 that diesel engine throttle opening is changed with excavator working condition changing. Diesel engine throttle opening is about 0.9 in mining condition and is 06 in formation condition.

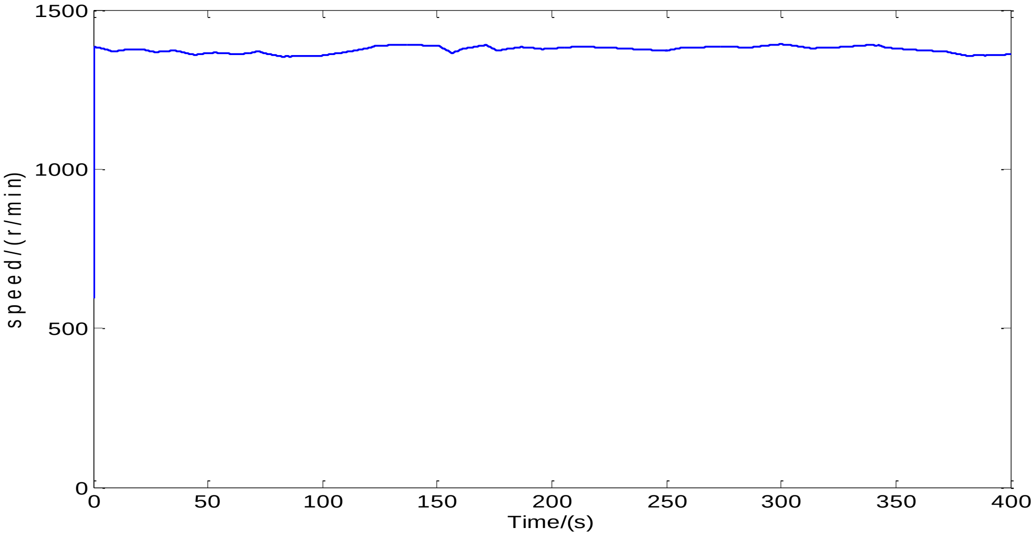

Figure 9. Diesel Engine Shaft Rotate Speed Curve

It can be seen from Figure 9 that diesel engine shaft rotate speed is almost constant during the whole working process, although hydraulic pump required power is changed obviously. So, the controller can reduce hybrid power system shaft rotate speed fluctuation.

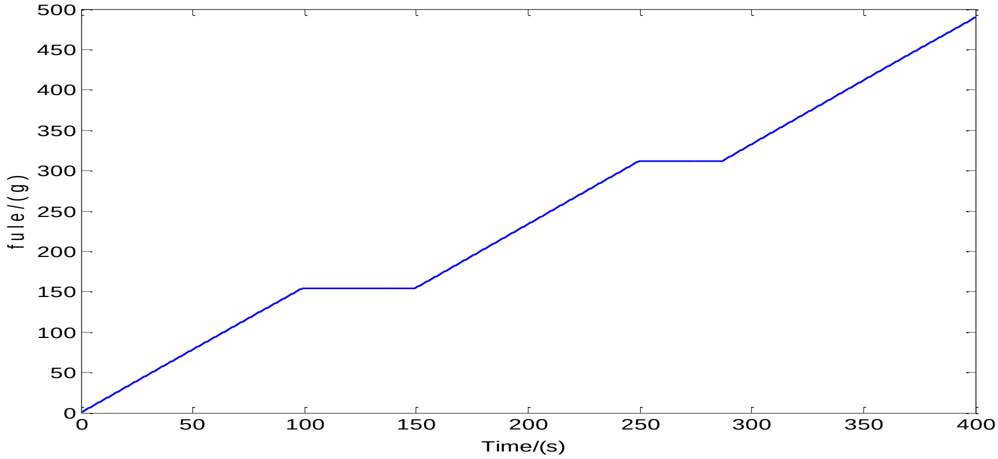

Figure 10. Diesel Engine Fuel Consumption Curve

It can be seen from Figure 10 that diesel engine fuel consumption rate is almost 1.5 g/s in mining condition and is zero in formation condition. Diesel engine fuel consumption rate is constant in mining condition, which means diesel engine is work in predefined high efficient area. So, the controller can reduce diesel engine fuel consumption.

5. Conclusions

Parallel hybrid excavator power system controller was designed. Controller input variables were set as hydraulic pump required torque, hydraulic pump rotate speed and battery SOC. controller output variables were set as diesel engine output torque and motor output torque. Simulation results show that the controller can realize coordination control between diesel engine and motor. Diesel engine shaft rotate speed is almost constant during the whole working process. Diesel engine can be work in high efficiency area with this controller.

Acknowledgements

This work was financially supported by Program for New Century Excellent Talents in University (NCET-11-0968); Project by Hunan Provincial Natural Science Foundation of China (14JJ5006); Aid program for Science and Technology Innovative Research Team in Higher Educational Institutions of Hunan Province.

.

References

[1] T. H. Peng, H. Y. Yang and F. Xin, “Chinese Journal of Mechanical Engineering”, vol.37, no.11, **(2001)**, pp. 50-53.
[2] W. R. Wu, D. W. Cheng and Z. Y. Cao, “Machine Tool & Hydraulic”, vol.35, no.9, **(2007)**, pp.212-214.
[3] Q. Xiao and Q. F. Wang, “China Journal of Highway and Transport”, vol.21, no.l, **(2008)**, pp.121-126.
[4] D. Y. Wang, G. Cheng, S. X. Pan and X. Lin, “Transactions of the Chinese Society for Agricultural Machinery”, vol.40, no.4, **(2009)**, pp.91-95.
[5] Z. H. Huang, Y. Xie, S. J. Liu and Y. Deng, “Journal of Hunan Institute of Engineering”, vol.22, no.3, **(2012)**,pp.21-24.
[6] T. L. Lin, Q. F. Wang, B. Z. Hu and W. Gong, “Automation in construction”, vol.19, no.8, **(2010)**, pp.1016-1026.
[7] Q. Xiao, Q. F. Wang and Y. T. Zhang, “Journal of Zhejiang University (Engineering Science)”, vol.41, no.3, **(2007)**, pp.480-453.
[8] G. Liu, D. C. Song, H. M. Chen and M. Chen, “Journal of Tongji University(Natural Science)”, vol.38, no.7, **(2010)**, pp.1079-1084.
[9] Q. Xiao, Q. F. Wang and Y. T. Zhang, “Automation in Construction”, vol.17, no.4, **(2008)**, pp.361-367.
[10] Q. F. Wang, Y. T. Zhang and Q. Xiao, “Chinese Journal of Mechanical Engineering”, vol.41, no.12, **(2005)**, pp.135-141.
[11] Z. H. Huang, Y. Xie and Y. Deng, “Construction Machinery and Equipment”, vol.43, no.11, **(2012)**, pp.25-28.

Authors

Xie Ya, she received her B.S degrees in computer science and technique from Central South University in 2006. She is working as a research staff in Hunan Institute of Engineering. Her current interest fields are computer simulation.

Huang Zhonghua, he received his Ph.D degrees in mechatronic engineering from Central South University in 2006. He is working as a research staff in Hunan Institute of Engineering. His current interest fields are hybrid excavator power system design.