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A STUDY ON AN ENERGY SAVING METHOD OF BOOM CYLINDER IN ELECTRO-HYDRAULIC EXCAVATOR

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Abstract*- Nowadays, the demand for energy saving and green emission of construction machinery, especially electro-hydraulic excavators, has been highly increased. As a result, hybrid system, which are promoted and successfully applied to automobile industry, is recently introduced to hydraulic excavators. This paper presents a new energy saving electro-hydraulic circuit design for the energy regeneration. In this system, a power storage component and an electrical battery is combined with an electro-hydraulic actuator using a hydraulic motor and an electric generator as energy convention component. The saving energy ability of boom cylinder in this circuit is already simulated by AMESim software. Besides that, energy can only be saved in Power Retraction Mode (PR). The natural frequency of the proposed energy recovery system is calculated based on the mathematical models. The effectiveness of the energy saving of boom cylinder in electro-hydraulic excavator is clearly proven by a series of simulation results in AMESim software.*

Keywords: Electro-Hydraulic Excavator (EHE), Motor, Saving Energy, Power, Generator.

1. INTRODUCTION

Hydraulic systems in a wide variety of forms are indispensable components of many modern work machines. All tractors, loaders, excavators and other heavy work machines utilize hydraulic actuated work implements with high energy consumption. Meanwhile, the cost of fuel has been increased rapidly and also, the pollution and global warming has become a serious problem day by day. Hence, the reductions of energy consumption and pollution become necessary and urgent demands. And hybrid electro-hydraulic vehicles are the efficiency solutions. Consequently, many researches on design and control of hybrid systems applied to hybrid electric vehicles have been done [1, 2].However, due to the complex working condition and frequent load changing, only 20% of the engine output power is utilized in a conventional type excavator [3]. Combined controls of actuators require distribution of flows and interflows, which increase loop loss. Meanwhile, the potential of working device, the kinetic energy of the turning body, and braking bodywork are converted into heat in the main throttle valve. This will lead to energy waste and temperature rising of system. The hydraulic component of system is damaged after the long time working. Therefore the energy recovery of working device has an important significance for improving energy utilization ratio for the conventional hydraulic excavator [4, 5]. Several researches on the energy saving of the conventional hydraulic excavator have been proposed [6, 7]. Furthermore, the most effective ways to create more efficient systems are matching the output power of pumps to the desired power of loads and regenerating the recoverable energy of actuators such as braking kinetic energy or gravitational potential energy.

Hybrid is a new power system which is widely used in automotive industry [8–10]. By using hybrid actuator, loss of energy can minimize. The hybrid system can thoroughly optimize the two energy configuration and take advantage of the benefits provided by them.

Fig.1: Hydraulic Excavator in modern industry

Normally, the actuation of hydraulic cylinder of the hybrid circuit in excavator consumes energy provide from two sources including a machine engine and another power source such as a fuel cell or battery. For example, a boom arm of an excavator will be lifted to a desired position by supplying hydraulic fluid to one or more hydraulic actuators working together. The energy required to raise the boom arm against the gravity force may be provided by pressurized hydraulic fluid from the work machine's hydraulic pump. On the contrary, when the boom arm is controlled to a lower position, the gravity force acting on the boom arm will cause it to lower, urging hydraulic fluid out of one side of the actuator. In traditional designs, the fluid flowing from the actuator is typically transitioned to a low pressure drain. In other words, when the boom arm is in a raised position, the system is considered as a comprising potential energy which is initially inputted to the system in the form of hydraulic energy to raise the boom arm. Meanwhile, when the boom arm is lowered, the hydraulic pressure is bled to a low pressure drain, and the potential energy residing in the raised boom arm will be lost.

To overcome the disadvantages of the traditional designs of excavators and to satisfy the current demands, this paper proposes one effective solution for excavator design using hybrid electro-hydraulic actuators. In this system, it is recognized that the potential energy derived from a gravity-assisted extension or retraction of a hydraulic actuator may be stored and later returned to the system as needed. Therefore, compared with the conventional system, propose Electro-Hydraulic Excavator (EHE) not only has a potential to improve the efficiency but also control the boom cylinder position with respect to reference. In EHE system controlling of position is a major fact. If saving energy is increased then boom down takes more time compare with low saving energy method. So that this proposed system is more efficient rather than conventional one.A series of simulation has been done to analysis the effectiveness of the proposed EHE system.

2. DESIGN OF THE SYSTEM SCHEME

Based on the excavator design purpose with higher working efficiency and more energy saving ability, a novel hybrid excavator is proposed in this research. It is the combination of electro-hydraulic actuators which the proposed hybrid actuator structure is shown in Fig. 2.

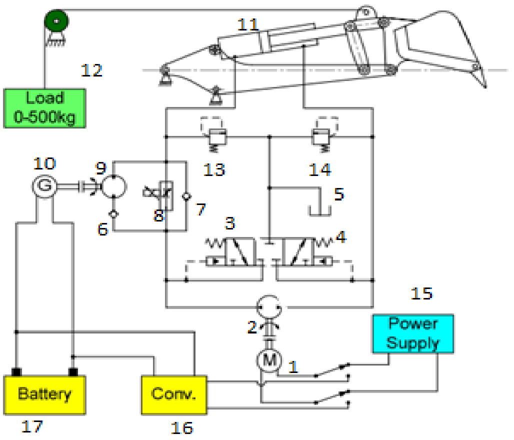


Fig.2: Proposed structure of Electro-Hydraulic Excavator

(1) Electric Motor
(2) Hydraulic Pump
(3, 4) Proportional flow control valve
(5) Tank
(6, 7) Check Valve
(8) Orifice
(9) Hydraulic Motor
(10) Generator
(11) Boom Cylinder
(12) Load
(13, 14) Relief Valve

In order to simplify the model, there is one assumption for the system.

i. There is not any energy loss in the hydraulic circuit and components but for the electrohydraulic direction control valve.

Run the simulation for a whole work period of the hydraulic excavator. The power of the pumps P_{in} and the power of the cylinder P_{out} are calculated by the following, respectively,

$$P_{in} = p_{in} \times q_{in} \tag{1}$$

$$P_{out} = p_{out} \times q_{out} \tag{2}$$

where, p_{in} and q_{in} are the pressure and the flow of the pumps and p_{out} and q_{out} are the pressure and flow rate of the cylinder.

It mainly consists of oil supply system, boom cylinder, control valves, and energy regeneration unit. The pump is driven by the engine and the motor. The pressure oil exporting from the pump was supplied to the boom cylinder system. When the boom cylinder piston is contracting, the excess energy is converted into electrical energy and stored in the battery. Compared with the engine power P_e and the load power P_l, there are three kinds of working conditions based on the load change.

i. When $P_e > P_l$, the pump is driven by the engine and the excess power of the engine is converted into electrical energy by the motor and stored in the battery. The motor is working as a generator in this working condition.

ii. When $P_e < P_l$, electrical energy stored in the battery is used to drive the motor. The engine and the motor drive the pump together.

iii. When the motor power $P_e > P_m > P_l$, the pump is driven by the motor independently and the engine is working in the idle state.

The working flow chart of the proposed system is shown in Figure 3.

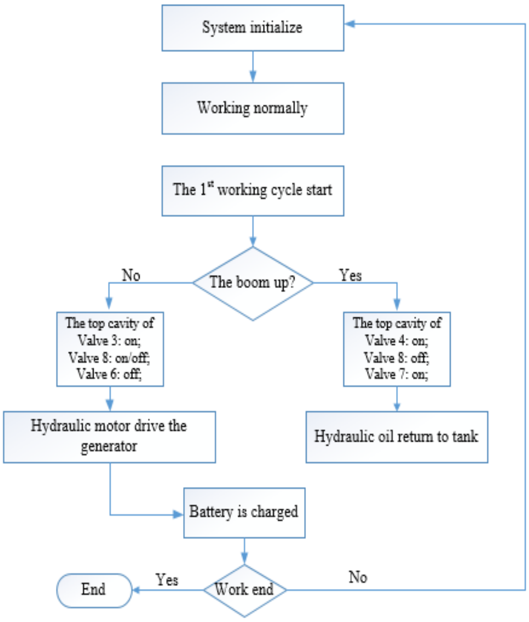


Fig.3: Working flow chart of the energy saving system

Based on the working condition of the excavator, the speed and torque of the generator will be tune by controlling the electric motor and the proportional valve to obtain the maximum efficiency and the highest saving energy. The setting parameters for the EHE are depicted in Table 1.

Table 1: Electro-Hydraulic Excavator parameters

Components	Value
Hydraulic cylinder	63*42*660 mm (Piston dia. * Rod dia. * Length of stroke)
Electric motor	1500 rpm
Hydraulic pump	34.3 cc/rev 2500rpm
Relief valve pressure	350 bar
Proportional flow valve	Max flow 45 l/min
Hydraulic Motor	39.5 l/min 900 rpm
Mass	500 Kg

3. MATHEMATICAL MODEL OF THE SYSTEM

3.1 Boom Cylinder

As shown in Figure 2, the dynamics of the piston of the boom cylinder can be expressed as

$$m_c \frac{dv_c}{dt} = F_l + P_2 A_2 - P_1 A_1 - f_c - B_c v_c \qquad (3)$$

where, m_c is the equivalent mass of the load, v_c is the velocity of the piston, F_l is the external force, P_1 and P_2 are the pressures in the large and small chamber of the single-rod cylinder, respectively, A_1 and A_2 denote the corresponding working areas, f_c is the coulomb friction force, and B_c is the combined coefficient of damping and viscous friction forces on the load and the rod. The value of v_c is the differential of the piston displacement x_c.

The flow equations of the two chambers of the cylinder are given by

$$\frac{V_1}{\beta_e}\frac{dP_1}{dt} = A_1 v_c - Q_1 - C_{ci}(P_1 - P_2) - C_{ce1}(P_1 - P_r) \qquad (4)$$

$$\frac{V_2}{\beta_e}\frac{dP_2}{dt} = Q_1 - A_2 v_c + C_{ci}(P_1 - P_2) - C_{ce2}(P_2 - P_r) \qquad (5)$$

where, V_1 and V_2 are the volumes of the two chambers of the cylinder, β_e is the effective bulk modulus of hydraulic oil, Q_1 and Q_2 are the flow rates of the two chambers, C_{ci} is the internal leakage coefficient of the cylinder, C_{ce1} and C_{ce2} are the external leakage coefficients of the two chambers, and P_r is the tank pressure. V_1 and V_2 are related to the displacement of the piston and can be expressed as

$$V_1 = V_{h1} - A_1 x_c \qquad (6)$$

$$V_2 = V_{h2} - A_2 x_c \qquad (7)$$

where, V_{h1} and V_{h2} are the initial volumes of the two chambers. The values of Q_1 and Q_2 are determined by the spool displacement and the pressure drops over the orifices of the valve as

$$Q_1 = K_{q1} x_v \sqrt{\Delta P}, \Delta P = \begin{cases} P_1 - P_3, x_v > 0 \\ P_s - P_1, x_v < 0 \end{cases} \qquad (8)$$

$$Q_2 = K_{q2} x_v \sqrt{\Delta P}, \Delta P = \begin{cases} P_1 - P_2, x_v > 0 \\ P_2 - P_3, x_v < 0 \end{cases} \qquad (9)$$

where, K_{q1} and K_{q2} are the flow gain coefficients of the metering orifices, x_v is the valve spool displacement, and P_s is the oil supply pressure.

The flow equation of the chamber between the valve and the hydraulic motor can be written as

$$\frac{V_3}{\beta_e}\frac{dP_3}{dt} = -\frac{\omega_m D_m}{2\pi} - C_{mt}(P_3 - P_r) + \begin{cases} Q_1, x_v > 0 \\ Q_2, x_v < 0 \end{cases} \qquad (10)$$

where, V_3 is the volume of the chamber, P_3 is the pressure in the chamber, ω_m is the rotational speed of the hydraulic motor and the electric generator which are coaxially coupled, D_m is the displacement of the hydraulic motor, and C_{mt} is the total leakage coefficient of the hydraulic motor [11].

3.2 Hydraulic Motor

The dynamics of the rotor of the regeneration unit can be expressed as

$$D_m(P_3 - P_4) = J\frac{d\omega_m}{dt} + b_m \omega_m + T_f + T_g \qquad (11)$$

where, ω_m the rotational speed of the hydraulic motor, J is the total moment of inertia of the regeneration unit, T_g is the electromagnetic torque of the generator, T_f is the coulomb friction torque, B_m is the combined coefficient of damping and viscous friction torques on the rotor, D_m is the displacement of the hydraulic motor, P_3 and P_4 are the inlet and outlet pressures of the motor.

Flow continuity equation of the motor can be written as

$$\begin{aligned} &Q_3 - C_{em}P_3 - C_{im}(P_3 - P_4) - D_m\omega_m = 0, \\ &D_m\omega_m + C_{im}(P_3 - P_4) - C_{em}P_2 - Q_4 = 0, \end{aligned} \quad (12)$$

where, C_{em} is the external leakage coefficients of the motor and C_{im} is the internal leakage coefficients of the motor.

Assuming that there is no loop loss in reversing valve, the flow equation of the chamber between the cylinder and the motor can be written as

$$A_1 v_c - C_{ic}(P_1 - P_2) - C_{ec}P_1 - C_{im}(P_1 - P_4) - \omega_m D_m = \frac{V}{\beta_e}\frac{dP_1}{dt}, \quad (13)$$

where, C_{ic} is the internal leakage coefficients of the cylinder, C_{ec} is the external leakage coefficient of the cylinder, V is the volume of the hydraulic oil between the boom cylinder and motor, and β_e is the volume elastic modulus.

4. SIMULATION OF THE EHE SYSTEM

In order to verify the energy saving efficacy of the proposed system, simulations with the proposed system have been carried out by using AMESim. It aims to validate the impact of energy recovery efficiency. Figure 4shows the AMESim model of the proposed system. The main setting parameters for the AMESim models are given in Table 1.In this system, its work by two modes.

i. Power Extension Mode (PE)
ii. Power Retraction Mode (PR)

Energy can save only in the PR mode and amount of saving energy depends on the orifice opening and closing situation.

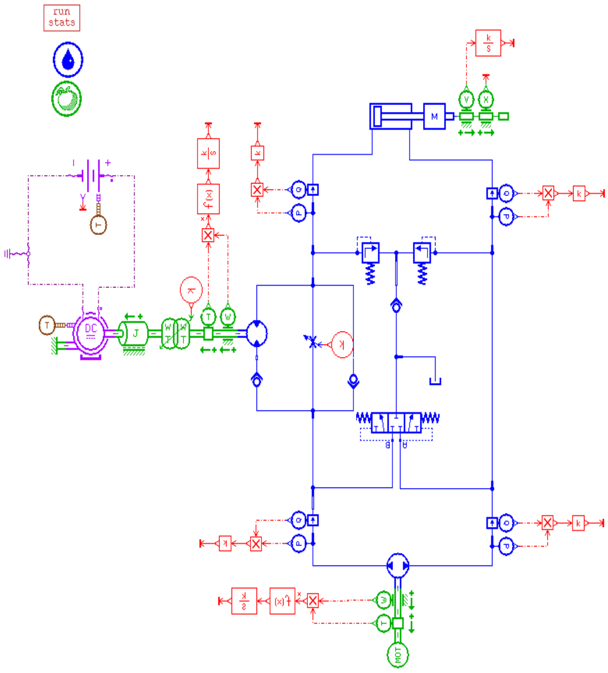


Fig.4: AMESim model of the proposed EHE system.

4.1 Power Extension Mode (PE)

When boom up that mode is called PE, the total working procedure is cleared in the Figure 5. Here, the cylinder of the hybrid system was simulated with 660 mm of full extension in case of 500 kg working load. Figure 6 depicts the results of this system. At this time energy can't save because engine need more power to lift boom with mass and as well as in this situation it work against gravitational force. All power is required to process this mode.

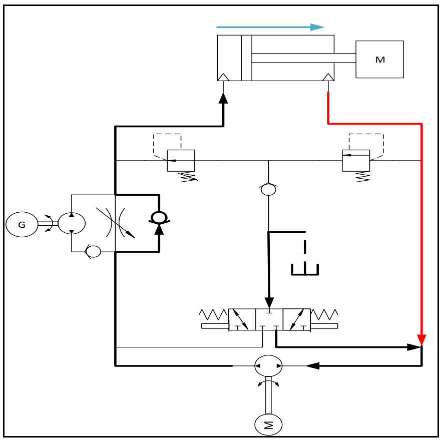


Fig.5: Working procedure of PE mode.

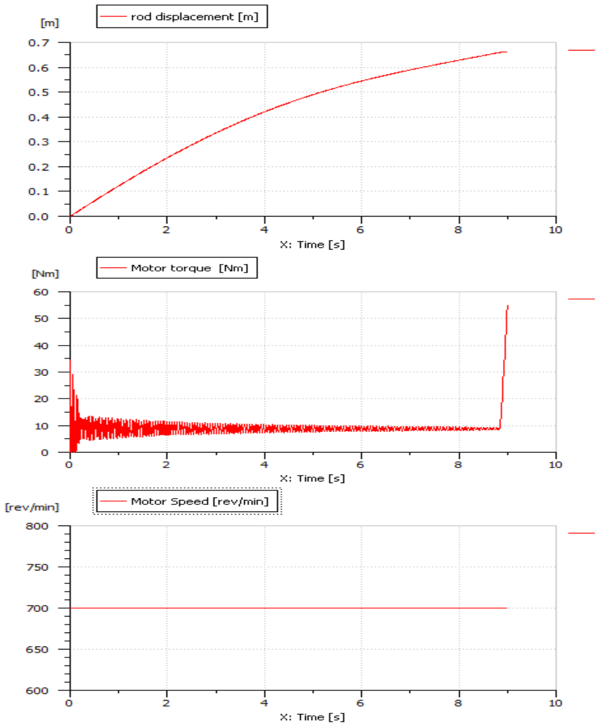


Fig.6: Cylinder power extension mode.

4.2 Power Retraction Mode (PR)

When boom down that mode is called PR, the total working procedure is cleared in the Figure 7. If orifice is fully closed, energy can save more but the main problem is time consuming. Boom down takes more time than boom up time. But orifice is fully opened then this problem is not occurred. Here, the cylinder of the hybrid system was simulated with 660 mm of full retraction in case of 500 kg working load. Figure 8 depicts the results of this system.In this mode energy can save and the saving energy depends on the orifice condition.

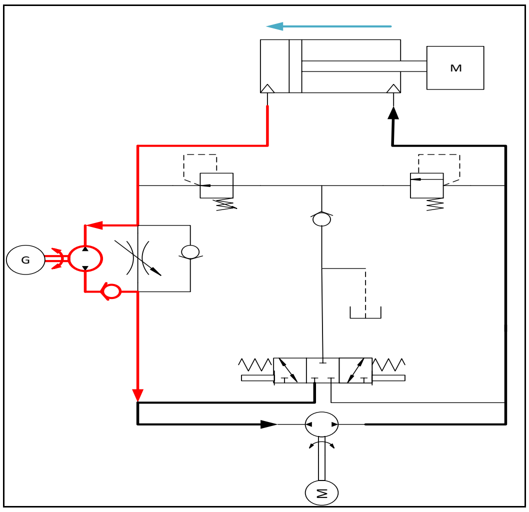
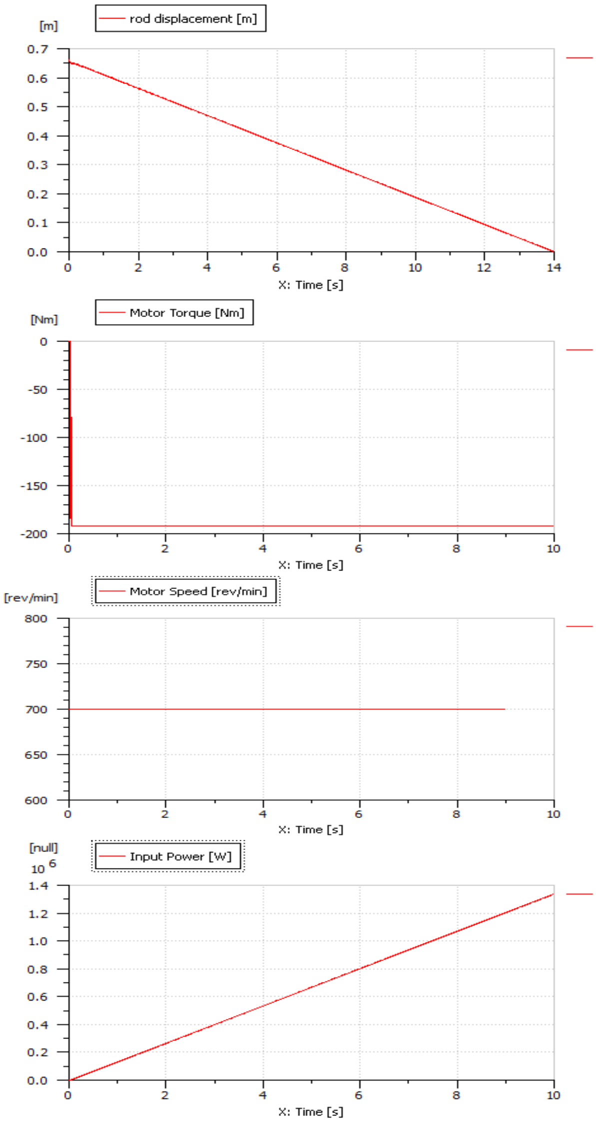


Fig.7: Working procedure of PR mode.



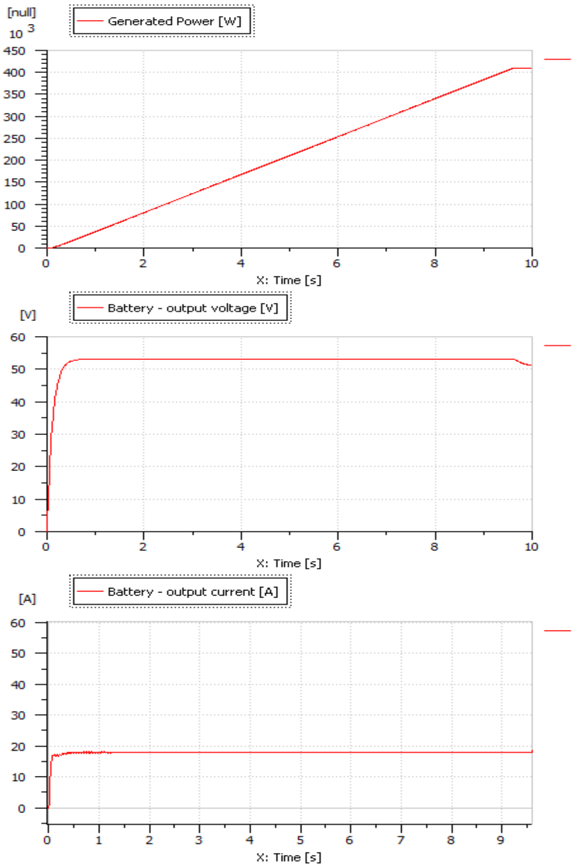


Fig.8: Cylinder power retraction mode.

4.3 Analyzing Result

The effectiveness of the proposed EHE system has been carried out in AMESim. AMESim is well-known, powerful software which accepts subprograms developed in other software. Therefore, the internal dynamicsof the different components can be neglected in the current study, as they are routinely built in AMESim. Here, several times simulation are performed.

As per mention before total saving energy depends on the orifice size. For this reason several times simulation has been done with different size of orifice and results are given in Table 2. Saving energy can be calculated by

$$Saving\ Energy = \frac{\sum Generated\ Power}{\sum Input\ Power} \times 100\% \qquad (14)$$

Table 2: Lookup table for different orifice values.

Orifice Size (%)	Input Power (KW)	Generated Power (KW)	Saving Energy (%)	Boom Down Time (Sec)
0	1874.39	409.00	21.82	14.00
10	1803.28	358.04	19.85	14.00
20	**1745.57**	**307.37**	**17.61**	**13.00**
30	**1673.12**	**267.7**	**16.00**	**12.00**
40	**1631.5**	**233.72**	**14.33**	**12.00**
50	1553.6	188.3	12.12	11.50
60	1517.35	154.91	10.21	11.00
70	1427.39	121.35	08.50	10.50
80	1409.9	97.2	06.90	10.50
90	1368.72	60.97	04.45	09.50
100	1313.18	35.56	02.70	9.00

Form lookup table it’s clear that depending on the orifice opening or closing, saving energy is increasing or decreasing. If orifice size keeps 0% (fully close) then saving energy percentage is 21.82 but it takes a little bit much time (14.00 sec) rather than boom up time. On the other hand if orifice sizes 100% (fully open) then saving energy percentage is too small 02.70 but it takes time (9.00 sec) as similar as boom up. So analyzing all of the value, it is clearly that the proposed electro-hydraulic excavator can operate with higher efficiency and has energy saving capability, if orifice size will choice between 20 to 40%. Because in this boundary the saving energy is satisfactory level as well as boom down time also in tolerate limit.

According to the mechanical characteristics of the generator, high efficiency depends on high speed and continuous rotation. If generator swirls continually, SOC (State of Charge) can rise smoothly. And this proposed system has that ability, it depicts from Figure 9. During a whole working period, the value of SOC reaches 50.18%. Finally, the energy stored in the battery.

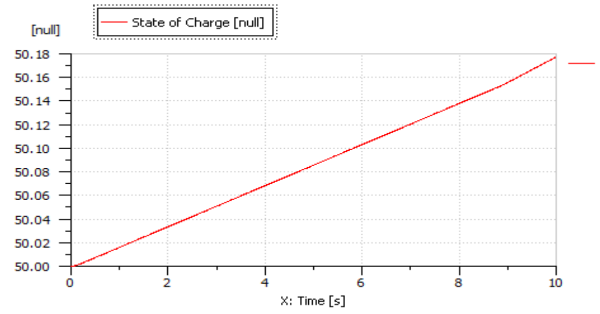


Fig.9: State of charge

5. CONCLUSION

In this paper, a novel energy regeneration electro-hydraulic excavator is newly proposed. In this system, a regeneration unit is used to take the place of a conventional pressure compensator to save energy. The mathematical models of the main components including boom cylinder, and hydraulic motor are built. The natural frequency of the proposed energy recovery system is calculated based on the mathematical models. In order to improve the natural frequency and response speed of the system, some measures should be taken based on the expression of the natural frequency.The effectiveness of the electro-hydraulic excavator is verified by means of simulation. The results prove that the proposed electro-hydraulic excavator can increase the working efficiency for the excavators.

As a result, when applying the proposed hybrid actuators into the real excavator, such as 5 tons excavator, the working effectiveness and the energy saving capability will be significantly increased when compared with the proposed system.

7. REFERENCES

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