에너지 절감 굴삭기 시스템을 위한 전자 MCV소개
Introduction of Independent Metering Valve for Energy Saving Excavator System

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1. Introduction

In the modern era, electro-hydraulic system plays a vital role in most of electric excavator (ELEX) where the hydraulic system is driven electrically. On the other hand this kind of hybrid system suffers from energy loss which leads for further improvement of the energy saving hydraulic circuit. In the formation of machinery field, manufacturers developed various kinds of machines based on hybrid concepts such as series, parallel or compound types of hybrid machines [1]. Considering the energy saving issue, traditional ELEX hydraulic circuit used accumulator for saving energy. In practice, using accumulator make the system bulky and difficult to control. Yoon and Truong [1] did research on energy saving excavator by fly-wheel and battery instead of using accumulator. However only one energy saving mode was realized by this method. Furthermore, Independent metering valve (IMV) system was analyzed by Amir [2]. This kind of circuit is ideal for ELEX as it does not require for additional accumulator to save energy. Here, the four independent proportional valve is considered in hydraulic circuits and controls the pressure of each chamber. Using this technique, different energy saving working mode can be realized successfully. On the other hand, these independent proportional valves are expensive also some energy loss was experienced during the operation inside the circuit.

Because of satisfying the recent demands of energy and also the inconvenience effect of conventional techniques, this paper proposes a new independent metering valve-based of energy saving circuit (NIMV) for electric excavator. Here, three electro hydraulic proportional valve (EHPV) and a simple directional control valve are used in this configuration to reduce system cost and energy consumption. This outline has the ability to overcome the control difficulties of the typical four valve IMV circuits during the same number of metering modes. As there is no connection between regenerative flow and high pressure flow, the proposed system is capable to save saving more energy than the conventional circuit of the ELEX. To ensure the overall performance, the exploration and control of the high-side regeneration extension mode and low-side regeneration retraction mode are compared to the conventional four valve configuration.
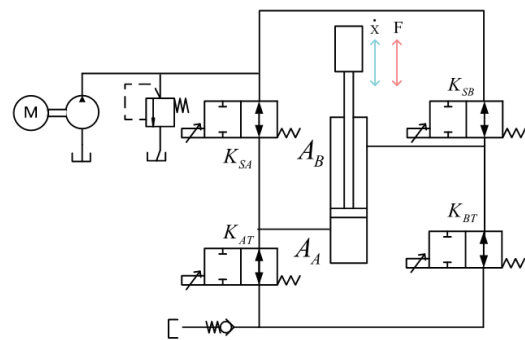

Fig. 1 CIMV system for ELEX

2. Conventional Four IMVs energy saving circuit

In the conventional IMV (CIMV) sketched in Fig. 1,contains four independent proportional valves and these are driven to follow the trajectory of the cylinder. Additionally five distinct metering modes [3] can be observed during operation. These are, (i) Power Extension mode (PE), (ii) Power Retraction

mode (PR), (iii) High-side Regeneration Extension mode (HSRE), (iv) Low-side Regeneration Extension mode (LSRE), (v) Low-side Regeneration Retraction mode (LSRR). The PE and PR are conceptually the same as the conventional proportional valve control hydraulic system. However it has benefit of independent metering by minimizing the restriction in the return line which cannot be realized by the proportional control valve.

In HSRE mode, the energy is saved by recirculating the flow in the high pressure side. In the other two modes the fluid recirculates to the low pressure side to save additional energy. For this two modes, check valve is necessary in order to build enough pressure in the CIMV system (Fig. 1). Though, the energy can be saved, on contrary some energy is still unsaved that consumed across the check valve. In addition, CIMV energy saving is lower than expected because of the direct connection between the recirculation flow and supply flow line. In addition CIMV system has four IMV valves that could increase the overall system cost.

3. New independent metering valve (NIMV) configuration for ELEX

In this section the NIMV circuit is proposed for ELEX system. The schematic diagram of the NIMV has been figured in Fig. 2. As seen in Fig. 2, the proposed circuit consists of three IMV valves and one conventional direction control valves. The entire working mode described in previous section can be achieved by this configuration. On the other hand reducing number of IMV valves means reducing cost and nonlinearities. The three IMV valves can be operated proportionally by controlling the orifice gain K_{SA}, K_{AB} and K_{BT} respectively. It is the task of the direction controlled valve to change the flow direction by fully opened and closing operation.

It should be pointed out that, there is no check valve has been placed throughout the NIMV circuit. Therefore, it is possible for the proposed circuit to

save the energy loss experienced by the CIMV system across the check valve.Now the different working mode of the NIMV system is studied as follows:
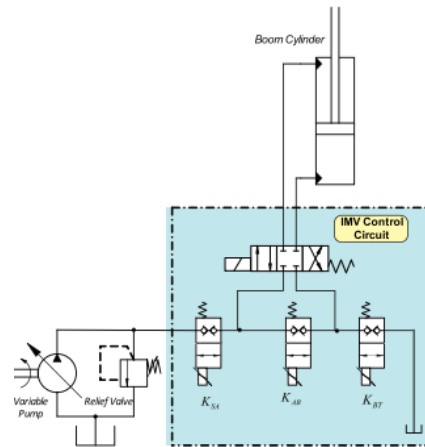

Fig. 2 Proposed NIMV configuration

3.1 Power Extension Mode

The power extension mode is figured in Fig. 3. As seen, The directional control valve is energized on the left side. The supply oil travels through the SA valve into the head side of the cylinder and the oil forced out from the rod side travels through the BT valve to the return line. In this configuration, SA and BT can be controlled independently same as in the PE mode of CIMV. Thus flow to the tank does not need to be always restricted.
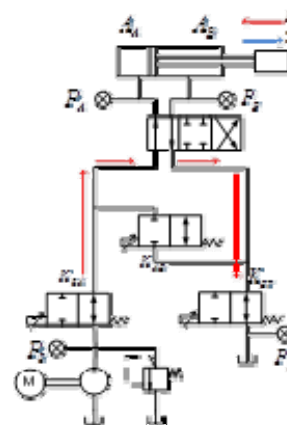

Fig. 3 PE mode ofthe NIMV system

3.2 PR Mode

This working mode is also conceptually same as

the PR of CIMV. Fig 4 displays the NIVM operation in PR mode. Firstly, the directional control valve is energized on the right side. Oil flow from the pump enters into the rod side of the actuator thorough the SA valve and then, the oil in the head side is forced out to the tank through the BT valve. These two valves can be independently controlled. Therefore in this mode, the same controlling capability is available as the power extension mode.
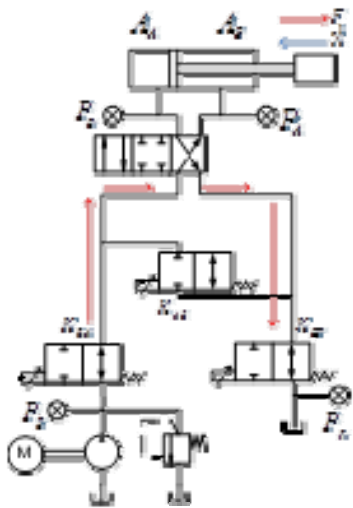

Fig. 4 PR mode of NIMV system

3.3 HSRE Mode

High side regeneration extension mode is quite similar to power extension mode except this mode has energy regenerative capacity. A schematic that describes this mode is shown in Fig 5. In this mode, the directional control valve is energized on the left side and, the other two valves: SA and AB are employed. The supply oil flows through the SA valve to the head side of the cylinder and consequently, the pressurized oil from the rod side of the cylinder is recirculated through the AB valve to the pump high pressure side. Due to the deference between areas of chambers, A and B ($A_A > A_B$), the flow from chamber B is less than the flow needed for chamber A to obtain certain velocity ($Q_A > Q_B$). Hence, an additional oil amount is needed from the pump to move the actuator. By doing the recirculation, this HSRE mode has the potential to save energy.
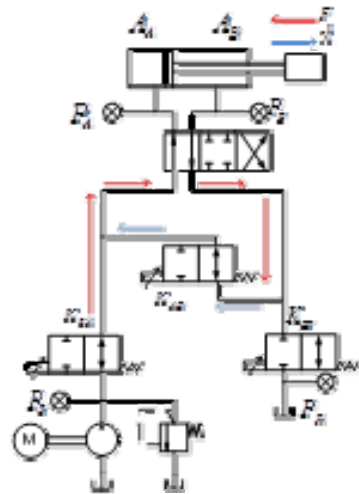

Fig. 5 HSRE mode of NIMV system

3.4 LSRE mode

Fig. 6 displays the operating concept of this mode. This mode is used to handle over running load during lowering. Same as the HSRE, the directional control valve is energized on the left side while the two valves, SA and AB are used to perform this operation. During the actuator extension, the low side generation is performed by circulating the low pressure oil at the rod chamber of the cylinder to its head chamber through valve AB. As discussed in the HSRE mode, the additional flow needs to be supplied by the pump to fulfill the flow requirement due to the cylinder chamber volume difference.
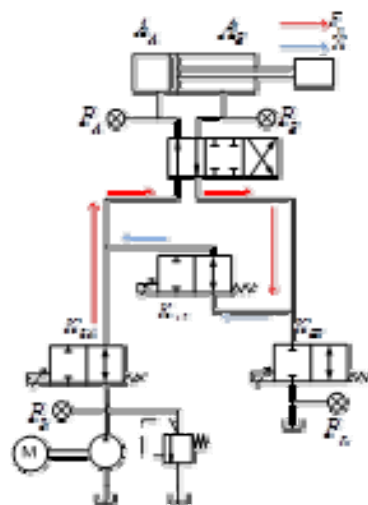

Fig. 6 LSRE mode of NIMV system

3.5 LSRR mode

This mode is applicable for overrunning load, which, for example, happens when lowering a load with gravity assistance. The principle is same as the LSRE mode except the oil flow direction. Here, the directional control valve is energized on the right side(see Fig. 7).
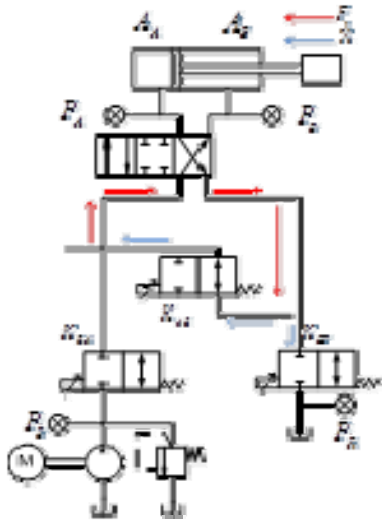

Fig. 7 LSRE mode of NIMV system

The oil flow coming out from the head chamber is circulated through valve AB into the rod chamber t cause the piston to retract. The extra oil flow due to the chamber volume difference then goes to tank through valve BT. This mode has high potential for saving energy because no pump flow is needed. Hence, it is called low side regeneration retraction mode.

4. Quasi-Static analysis of NIMV

In this section, the quasi static system modeling of the NIMV is carried out. For the system modeling, It is assumed that the system dynamics are relatively slowly changing with respect to the control system. The supply line, return line and different work port capacitances are also ignored.

4.1 PE mode model

A schematic of simplified PE mode is shown in Fig 8. Here the equivalent pressure source is P_{EQ}

and an equivalent valve conductance K_{EQ}. The both active valves are represented as variable orifice restrictions. The valve conductance coefficient K_{SA} and K_{BT}, can be controlled separately by the controller to obtain independent metering [4]. The flows across the inlet and outlet orifice of the cylinder are given by the following orifice equation.

$$Q_A = K_{SA}\sqrt{\Delta P_1} = K_{SA}\sqrt{P_S - P_A} = A_A \dot{x}; \dot{x} > 0 \tag{1}$$

$$Q_B = K_{BT}\sqrt{\Delta P_2} = K_{BT}\sqrt{P_B - P_R} = A_B \dot{x}; \dot{x} > 0 \tag{2}$$

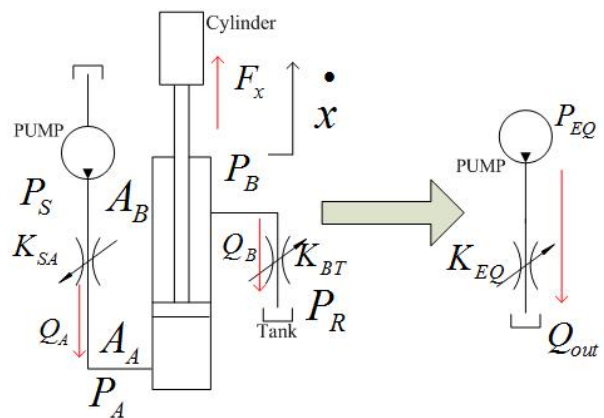Fig. 8 PE mode model

By rearranging Eq. (1) and Eq. (2)

$$P_A = P_S - \frac{Q_A^2}{K_{SA}^2} \tag{3}$$

$$P_B = \frac{Q_B^2}{K_{BT}^2} + P_R \tag{4}$$

Considering the sum of forces is equal to Fx , the following equation can be written as:

$$F_X = P_B A_B - P_A A_A \tag{5}$$

By substituting Eq. (3) and Eq. (4) into the Eq. (5) we obtain

$$\left(P_S - \frac{Q_A^2}{K_{SA}^2}\right)A_A - \left(\frac{Q_B^2}{K_{BT}^2} + P_R\right)A_B + F_X = 0 \tag{6}$$

The following equation is formed after rearranging the Eq. (6)

$$P_S A_A - P_R A_B - \dot{x}^2 \left(\frac{A_A^3}{K_{SA}^2} + \frac{A_B^3}{K_{BT}^2} \right) + F_X = 0 \tag{7}$$

By introducing the ratio of areas as Eq. (8) the equivalent valve conductance will be same as Eq. (9) [4]. That is,

$$R = \frac{A_A}{A_B} \tag{8}$$

$$K_{EQ} = \frac{K_{SA} K_{BT}}{\sqrt{K_{SA}^2 + R^3 K_{BT}^2}} \tag{9}$$

From Eq. (7), Eq. (8) and Eq. (9) we find,

$$R P_S - P_R - \frac{\dot{x}^2 A_B^2}{K_{EQ}^2} - R P_A + P_B = 0 \tag{10}$$

Eq. (10) is then rearranged for getting the Eq. (11) below

$$Q_B = \dot{x} A_B$$
$$= K_{EQ} \sqrt{R(P_S - P_A) + (P_B - P_R)} ; \dot{x} > 0 \tag{11}$$

By comparing the Eq. (11) term equivalent pressure PEQ is calculated as,

$$P_{EQ} \equiv R(P_S - P_A) + (P_B - P_R) \tag{12}$$

Eq. (12) and Eq. (2) are to be substituted into Eq. (11) leads.

$$Q_B = K_{EQ} \sqrt{P_{EQ}} = \dot{x} A_B ; \dot{x} > 0 \tag{13}$$

For controlling purpose the velocity represents as commanded velocity, which is represented as $\dot{x}_c$

$$K_{EQ} = \frac{Q_B}{\sqrt{P_{EQ}}} = \frac{\dot{x}_c A_B}{\sqrt{P_{EQ}}} ; \dot{x}_c > 0 \tag{14}$$

As both Eq. (13) and Eq. (14) are linearly proportional to the K_{EQ}, Eq. (11) or Eq. (14) can be used for calculating the K_{EQ}. That is:

$$P_{S\_SET} = \frac{R P_A - P_B + P_R}{R} + \frac{\dot{x}^2 A_B^2}{R K_{EQ}^2} \tag{15}$$

From [3], it is proven that for calculating numerical solution for valve conductance coefficient, the ratio of the area R could be represented as:

$$\frac{K_{SA}}{K_{BT}} = R^{3/4} \tag{16}$$

For calculating each valve conductance Eq. (16) is substituted into Eq. (9) and following valve conductance equations are obtained. By using those control equations it is possible to control the opening of the each valve with respect to equivalent pressure and equivalent valve conductance.

$$K_{SA} = K_{EQ} \sqrt{R^{3/2} + R^3} \tag{17}$$

$$K_{BT} = K_{EQ} \sqrt{1 + R^{3/2}} \tag{18}$$

4.2 PR mode model

The schematic diagram for modeling of PR mode is shown in Fig. 9. Using the same procedure, one can find the equivalent valve conductance for controlling the opening of the two active valves which can be formulated as,

$$P_R A_A - P_S A_B + \dot{x}^2 \left(\frac{A_B^3}{K_{SA}^2} + \frac{A_A^3}{K_{BT}^2} \right) + F_X = 0 \tag{19}$$

$$P_{EQ} = R(P_A - P_R) + (P_S - P_B) \tag{20}$$

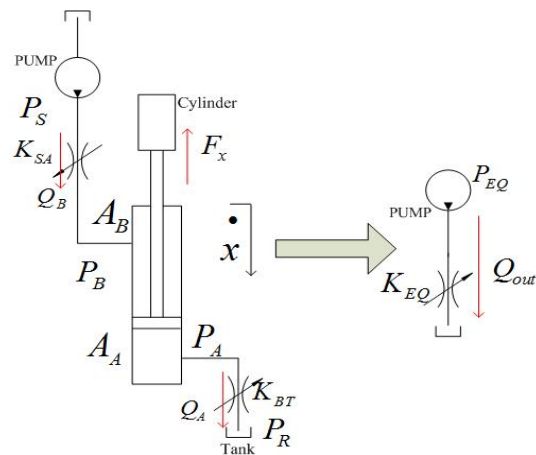$$K_{EQ} = \frac{Q_B}{\sqrt{P_{EQ}}} = -\frac{\dot{x}_c A_B}{\sqrt{P_{EQ}}} ; \dot{x}_c < 0 \tag{21}$$

Fig. 9 PR mode model

$$K_{SA} = K_{EQ}\sqrt{R^{9/2}+1} \qquad (22)$$

$$K_{BT} = K_{EQ}\sqrt{R^{1/2}+R^{-3/2}} \qquad (23)$$

4.3 HSRE mode model

A schematic diagram is shown in Fig. 10 used for modeling the HSRE mode.
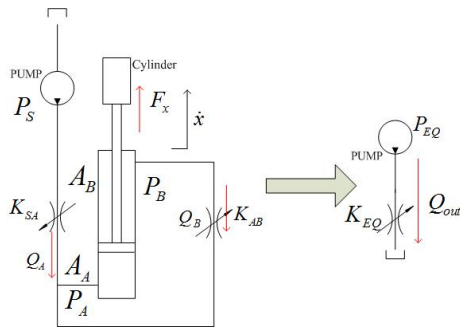

Fig. 10 HSRE mode model

Using similar procedure one can find,

$$P_S A_A - P_S A_B - \dot{x}^2\left(\frac{A_A^3}{K_{SA}^2}+\frac{A_B^3}{K_{AB}^2}-\frac{A_A^2 A_B}{K_{SA}^2}\right)+F_X = 0 \qquad (24)$$

$$P_{EQ} = R\left(P_S - P_A\right)+\left(P_B - P_S\right) \qquad (25)$$

$$K_{EQ} = \frac{Q_B}{\sqrt{P_{EQ}}} = \frac{\dot{x}_c A_B}{\sqrt{P_{EQ}}}; \dot{x}_c > 0 \qquad (26)$$

$$K_{SA} = K_{EQ}\sqrt{R^{3/2}+R^3-R^2} \qquad (27)$$

$$K_{AB} = K_{EQ}\sqrt{1+R^{3/2}-R^{1/2}} \qquad (28)$$

4.4 LSRE mode model

Low side regeneration extension modeling is similar to the high side regeneration extension mode. HSRE is called as LSRE when the load force direction is the same the direction cylinder motion. From the schematic diagram shown in HSRE mode in Fig 10, LSRE mode can be easily modeled. The final valve conductance can be calculated as follows,

$$P_{EQ} = R\left(P_S - P_A\right)+\left(P_B - P_S\right)$$
$$Q_B = \dot{x}A_B$$
$$= K_{EQ}\sqrt{R\left(P_A - P_S\right)+\left(P_S - P_B\right)}; \dot{x} > 0 \qquad (29)$$

$$K_{SA} = K_{EQ}\sqrt{R^{3/2}+R^3-R^2} \qquad (30)$$

$$K_{AB} = K_{EQ}\sqrt{1+R^{3/2}-R^{1/2}} \qquad (31)$$

4.5 LSRR mode model

Using a similar type of schematic diagram and quasi-static assumptions simplified Low Side Regeneration Retraction mode can be modeled.Hence, we can easily calculate each acting valve conductance by,

$$Q_B = -\dot{x}A_B$$
$$= K_{EQ}\sqrt{R\left(P_S - P_A\right)+\left(P_B - P_S\right)}; \dot{x} < 0 \qquad (32)$$

$$P_{EQ} = R\left(P_S - P_A\right)+\left(P_B - P_S\right) \qquad (33)$$

$$K_{SA} = K_{EQ}\sqrt{R^{9/2}-R^{5/2}+1} \qquad (34)$$

$$K_{AB} = K_{EQ}\sqrt{R^{-3/2}+R^3+R} \qquad (35)$$

Table 1 System parameters

Parameters	Specification	Value
Cylinder	Piston diameter× Rod diameter × Length of stroke	63 mm× 42 mm× 0.85m
Fluid Properties	Density	850 kg/m^3
	Bulk modulus	17000 bar
Hydraulic Pump	Pump displacement	34.5 cc/rev
	Pump Speed	2400 rev/min
Relief valve	Cracking pressure	300 bar
Throttle valve	Cross sectional area at maximum opening	5 mm^2
Direction Control valve	Damping ratio	0.8

5. Simulation results.

The effectiveness of the proposed NIMV configuration over the CIMV has been carried out in AMEsim for two energy saving cases: HSRE mode and LSRR mode. AMEsim is well-known,

powerful software which accepts subprograms developed in other software. In this paper, the NIMV and CIMV hydraulics model has been made in AMEsim using required valve blocks from the AMEsim library.Therefore, the internal dynamics of the different components can be neglected in the current study, as they are routinely built in AMEsim. Additionally, the valve opening dynamics for the two models were coded under the Simulink environment and adopted in AMEsim software. Finally, the co-simulation AMESim–Simulink model of the New IMV (NIMV) to drive the boom cylinder of the ELEX is shown in Fig. 11, respectively.For each configuration, the setting parameters for the simulations are listed in Table
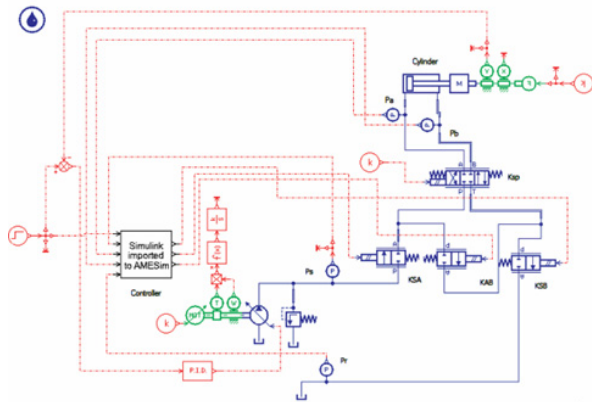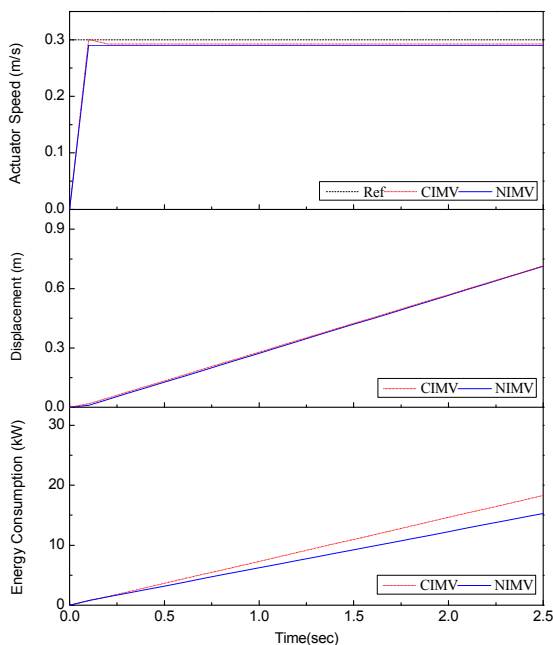

Fig. 11 Proposed NIMV AMEsim model

Fig. 12 HSRE mode simulation

1.The conductances of these valves were defined based on the reference speed and feedback pressure signals Pa, Pb, Ps, and Pr of the hydraulic circuits.
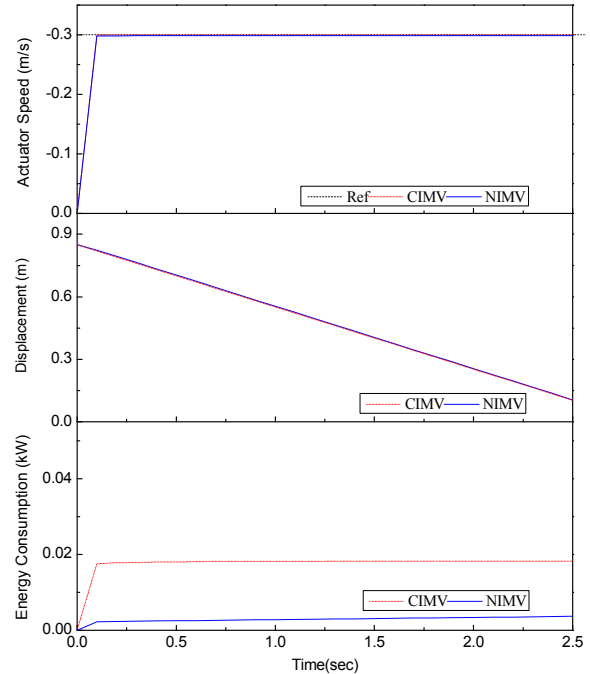

Fig. 13 LSRR mode simulation

Simultaneously, the pump displacement was controlled by a Proportional-Integral-Derivative (PID) controller to save power from the pump.The PID control parameters were determined for each working mode by trial and error. The load conditions are 20 kN for HSRE mode and 15 kN for LSRR mode.

Finally, from the energy consumption comparison between the CIMV and the NIMV configuration (Figs. 12 and 13), it is very clear that the performance of the NIMV configuration is much better that of the CIMV configuration. The NIMV configuration shows 16.43% and 63.63% energy saving performance for HSRE and LSRR, respectively.

6. Conclusion

In this paper, an innovative independent metering valve based energy saving hydraulic configuration has been presented for electric excavator.

Mathematical models for different regenerative modes have been developed. To verify the modeling and control equation, a typical hydraulic circuit was built in AMESim. Embedded Matlab programing was used for control purpose. The performance of the new configuration was compared to the four-valveindependent metering system, and the results were positive. As future work, this system can easily be tested by using a high-frequency, on-off hydraulic valve in the electric excavator test rig.

Reference

1) J. I. Yoon, D. Q. Truong, and K. K. Ahn, "A generation step for an electric excavator with a control strategy and verifications of energy consumption", International Journal of precision engineering and manufacturing, Vol. 14, No 5, pp.755~766, 2013.

2) A. Shenouda, "Quasi-static hydraulic control systems and energy savings potential using independent metering four-valve assembly configuration," PhD Thesis, Georgia Institute of Technology, 2006.

3) K. Tabor, "Optimal velocity control and cavitation prevention of a hydraulic actuator using four valve independent metering," SAE Technical Paper, No 2005-01-3620, 2005.

4) N.D. Vaughan, and J.B. Gamble, "The modeling and simulation of a proportional solenoid valve," Journal of Dynamics System measurement and Control, Vol. 118, No 1, pp. 120~125, 1996.

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