Co-simulation of Energy regulation based variable-speed electrohydraulic drive

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Abstract

The variable-speed electrohydraulic drive, which can achieve similar energy efficiency as volume drive, has some excellent features. But the main disadvantages, which are slow response and poor low-speed performance, limit its development. The energy regulation based variable-speed electrohydraulic drive is a good solution to solve these problems by adding an energy regulation device and a main-circuit throttling valve into the system. However, it is a multiple-input multiple-output control system, coupled with strong nonlinear and some parameters of volatility and uncertainty, which make the control strategy complicated. To test the performance of the new drive, co-simulations of AMESim and Matlab/Simulink are implemented. The co-simulation integrates the advantages of AMESim as well as Matlab/Simulink. It is very suitable for complicated hydraulic system. And the simulation results have showed the performance of energy regulation based variable-speed drive.

Keywords: Co-simulation; Variable-speed; Energy regulation; AMESim; Simulink

1. Introduction

The variable-speed electrohydraulic drive, which adjusts the pump’s output flowrate via adjusting the motor’s speed, has been greatly studied and improved these years [1-8]. And it has been used in hydraulic elevator, injection machine and fan drive et al. The variable-speed electrohydraulic drive is very popular...
due to its high energy efficiency as volume drive. In addition, it has some good features such as wide speed-range and high reliability. However, its most crucial disadvantage is slow-response which is due to the big inertia of motor-pump. To improve the poor low-speed performance, a flow valve is added to compose the compound drive of variable-speed and valve control. But it is helpless to improving the acceleration response [6-8].

Adding an energy regulation device (ERD) into the compound drive is a good solution to this problem. If the system is accelerating while the motor-pump can’t speed up quickly due to its big inertia, the ERD releases energy so as to improve the response. If the system is decelerating while the motor-pump can’t slow down quickly, the ERD absorbs redundant hydraulic oil in the system in order to reduce the restriction loss and overflow loss. In other cases, the ERD is closed.

To test the performance of the new drive, the co-simulation of AMESim and Simulink is carried out. It combines with the advantages of hydraulic models in AMESim and control calculations in Matlab/Simulink. The first part introduces the principle of energy regulation based variable-speed drive. The second part explains the energy regulation strategy, which is be used in simulation. And the third part discusses the co-simulation method, the simulation results.

2. Principle of Energy regulation based variable-speed drive

Fig.1 shows the energy regulation based variable-speed electrohydraulic valve-controlled motor drive system. As the main power source, the inverter drives the fixed-displacement pump via the three-phase asynchronous motor. The ERD, which is composed of an accumulator, a proportional throttle valve and a relief valve, is mainly used as an auxiliary power source. In the ERD, the accumulator is be used to storage energy, the proportional throttle valve controls the flowrate absorbing or releasing by the ERD, the relief valve is used as a safety valve. The proportional directional valve controls the hydraulic motor axis’s rotation and speed.

![Diagram of Energy regulation based variable-speed electrohydraulic valve-controlled motor drive system](image)

Fig.1 Energy regulation based variable-speed electrohydraulic valve-controlled motor drive system

Fig.2 shows the system control diagram. The ERD, whose function depends on the internal and external pressure, is a semi-active device. The same control signal to the ERD may cause different
absorbing or releasing oil consequents. So $p_s$ and $p_e$ should be input to the controller as feedback parameters.

In the view of the controller, the energy regulation based variable-speed drive is a MIMO system. There are four inputs, the motor command-speed, actual-speed, $p_s$ and $p_e$. The outputs are inverter frequency, the input voltages of proportional directional valve and proportional throttle valve.

There are two power sources in the system, the main power source: inverter-motor-pump and the auxiliary power source: ERD. The general control scheme is described as follows [6-7].

1. If $n_m < n_{in}$, $f_{in}$ will increase. If $p_e > p_s$, the ERD will be open to release oil in order to improve system acceleration response. The proportional directional valve will be input its maximal current.

2. If $n_m > n_{in}$, $f_{in}$ will decrease. If $p_e < p_s$, the ERD will be open to absorb system redundant oil so as to reduce restriction loss and overflow loss. The proportional directional valve will reduce its opening.

3. In other cases, the ERD will be closed. The inverter and proportional directional valve control the hydraulic motor together.

3. Co-simulation of AMESim and Matlab/Simulink

AMESim (Advanced Modeling and Simulation Environment for Systems Engineering) offers a complete 1D simulation suite to model and analyze multi-domain, intelligent systems and to predict their multi-disciplinary performance. The components of the model are described by analytical models representing the hydraulic, pneumatic, electric or mechanical behaviour of the system. To create the system simulation model in AMESim, the user can make use of a large set of validated libraries of pre-defined components from different physical domains. The modeling and simulation process is divided into four steps: (1) build the program model → (2) decide the model complexity → (3) set the model parameters → (4) simulation and analyze.

The MathWorks Simulink is developed for dynamic systems and embedded systems by multi-domain simulation and model-based design tools. It can be a variety of time-varying systems such as communications, control, signal processing, video processing and image processing system. However, Simulink does not have a specifically toolbox for fluid simulation. When create their own models, the users should be experienced in complex hydraulic system.

The co-simulation has some outstanding advantages: (1) Make full use of the two tools, where AMESim focuses on the hydraulic part and Matlab/Simulink concentrates on the control part; (2) Modeling, simulation as well as system analysis capabilities can be continued in AMESim and Matlab / Simulink respectively; (3) Provides a standard interface and the joint simulation interface. And the users can determine their own AMESim and Simulink algorithm types; (4) Simple operation. It can greatly reduce operator workload, and achieve good simulation results.

The co-simulation interface of AMESim and Matlab/Simulink is achieved by connecting the menu icon of creating output in AMESim to the function in Simulink. The concrete process can be divided into
three steps: (1) Generates a function where is complied, parameter set in AMESim. The function can be used in Simulink. (2) Put the function into the Simulink model. (3) Co-simulation.

To test the performance of energy regulation system, some simulations are implemented. Furthermore, valve-control drive, conventional variable-speed drive and variable-speed&valve compound drive are also carried out the similar studies[7-8].

(1) Valve control drive. The ERD is closed. The motor speed is not be regulated. It maintains 1500 r/min all the time. The proportional directional valve controls the motor speed.

\[ u_d(k) = \begin{cases} 10 & e(k) > 0 \\ \min\left(\max\left(k_{d1} e(k)+\min\left(\sum_{i=0}^{k_{d2}} e(i),0\right),10\right)+k_{d3}\left[e(k)-e(k-1)\right],0\right) & e(k) \leq 0 \end{cases} \]

Where \( e(k) = n_{in}-n_{m} \).

(2) Variable-speed drive. The ERD is closed. The hydraulic motor speed is adjusted via changing the inverter frequency. The proportional directional valve, which controls the hydraulic motor rotation only, keeps its maximum opening all the time.

\[ f_m = \min\left(\max\left(K_{m1} n_m + u(k)\right),0\right),50 \]

Where \( u(k) = k_{p1} e(k)+k_{p2} \sum_{i=0}^{k_{p3}} e(i)+k_{p4}\left[e(k)-e(k-1)\right] \), \( k_{p2} = \begin{cases} 1 & e(k) \leq e_0 \\ 0 & e(k) > e_0 \end{cases} \).

(3) Compound drive. The ERD is closed. The proportional directional valve and the motor control the hydraulic motor together. The control expression of the inverter is the same as Equ.(2). And the control expression of the proportional directional valve is the same as Equ.(1)

(4) Energy regulation based variable-speed drive. The control expression of the inverter is also the same as Equ.(2). And the control expression of the proportional directional valve is also the same as Equ.(1). The expression of the ERD is:

\[ u_g(k) = \begin{cases} k_{p1} e(k)+k_{p2} \sum_{i=0}^{k_{p3}} e(i)+k_{p4}\left[e(k)-e(k-1)\right] & e(k) > 0, \quad p_e > p_s \\ \min\left(\max\left(k_{d1} e(k)+\min\left(\sum_{i=0}^{k_{d2}} e(i),0\right),10\right)+k_{d3}\left[e(k)-e(k-1)\right],0\right) & e(k) \leq 0, \quad p_e < p_s \\ 0 & Others \end{cases} \]

Where \( k_{d2} = \begin{cases} 1 & e(k) \leq e_i \\ 0 & e(k) > e_i \end{cases} \).

Fig.3 shows the co-simulation interface. It shows that the control part in Simulink can be called by AMESim as a common module.
In this paper, the number 1~4 expresses the valve drive, variable-speed drive, compound drive and energy regulation drive respectively without special explanation.

To compare performances, the control expression of each controlled-object in the above three drive system is the same as it in this system. Corresponding, the conditions of simulation are all the same, as well as the control parameters. Table.1 shows the main parameters of this system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC motor nominal power</td>
<td>15kW</td>
</tr>
<tr>
<td>AC motor nominal speed</td>
<td>1500r/min</td>
</tr>
<tr>
<td>Pump displacement</td>
<td>20mL/r</td>
</tr>
<tr>
<td>Hydraulic motor displacement</td>
<td>30mL/r</td>
</tr>
<tr>
<td>Accumulator volume</td>
<td>6.3L</td>
</tr>
<tr>
<td>Accumulator precharge pressure</td>
<td>2MPa</td>
</tr>
<tr>
<td>Effective bulk modulus of hydraulic oil</td>
<td>700MPa</td>
</tr>
</tbody>
</table>

4. Simulations and Discussions

Fig.4 shows the step response of the four drive systems. The response of variable-speed drive with an ERD is the fastest. It is even faster than the valve control system due to the large flow released by the ERD. When the system accelerates, the ERD releases oil to compensate the deficiency of system flowrate demand. The curves of 2 and 3 are almost the same, because their accelerations all depend on the motor speed’s increase.
Fig. 4 Step response of co-simulation (load-pressure=2.5MPa)

Fig. 5 shows the power curves. The power curve of valve control system is always the highest. It decreases when the proportional throttle valve is open. The other three curves almost coincide.

Fig. 5 Power in simulation (load-pressure=2.5MPa)

Furthermore, the sinusoidal command-speed (0.2Hz) experiments are also carried out under variable load-pressure. Table 2 shows the mean square error (MSE). It can be seen that this system has smaller MSE than conventional variable-speed drive and compound drive under all load-pressure range, which shows its good tracking performance.

<table>
<thead>
<tr>
<th>Load-pressure</th>
<th>No-load</th>
<th>2.5MPa</th>
<th>3.5MPa</th>
<th>5MPa</th>
<th>6MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve-control</td>
<td>326.6</td>
<td>584.5</td>
<td>633.4</td>
<td>1072.6</td>
<td>1551.8</td>
</tr>
<tr>
<td>Variable-speed</td>
<td>927.9</td>
<td>856.5</td>
<td>892.3</td>
<td>919.3</td>
<td>869.5</td>
</tr>
<tr>
<td>Compound drive</td>
<td>870.0</td>
<td>9397</td>
<td>869.9</td>
<td>888.5</td>
<td>967.9</td>
</tr>
<tr>
<td>Energy regulation based variable-speed</td>
<td>523.6</td>
<td>551.1</td>
<td>548.7</td>
<td>594.4</td>
<td>538.9</td>
</tr>
</tbody>
</table>
MSE = \frac{1}{n} \sum_{k=1}^{n} (n_m(k) - n_a(k))^2

Where \( n \) is the total sampling number.

Table 3 shows the mean power under variable load-pressure. The power of valve drive system is always the biggest. And the power data are almost the same in other three drive systems. Because the three drive systems are belong to volume-control drive in essential, where the pump outlet pressure is in accordance with the load-pressure.

<table>
<thead>
<tr>
<th>Load-pressure</th>
<th>No-load</th>
<th>2.5MPa</th>
<th>3.5MPa</th>
<th>5MPa</th>
<th>6MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve-control</td>
<td>5.19</td>
<td>5.11</td>
<td>5.06</td>
<td>4.96</td>
<td>4.99</td>
</tr>
<tr>
<td>Variable-speed</td>
<td>0.38</td>
<td>0.68</td>
<td>0.95</td>
<td>1.41</td>
<td>1.73</td>
</tr>
<tr>
<td>Compound drive</td>
<td>0.32</td>
<td>0.62</td>
<td>0.91</td>
<td>1.35</td>
<td>1.63</td>
</tr>
<tr>
<td>Energy regulation based variable-speed</td>
<td>0.35</td>
<td>0.64</td>
<td>0.92</td>
<td>1.35</td>
<td>1.64</td>
</tr>
</tbody>
</table>

5. Conclusions

A co-simulation method for energy regulation based variable-speed drive using AMESim and Matlab/Simulink is discussed. The simulation results show that the energy regulation drive has a good response. And the so-simulation of AMESim and Matlab/Simulink can be used in complex hydraulic systems.

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