

Modeling & parameterization of Directional Control Valves using Matlab-Simulink/Sim Hydraulics

Vijay Mishra¹, Dr.Sunil Chandel²

¹PG Student, Department. of Mechanical Engg., DIAT,(DU),Pune, India

² Assistant Professor, Department. of Mechanical Engg. DIAT, (DU),Pune,India

Abstract

One of the key components of all modern hydraulic are Directional Control Valves (DCV) which are used in fluid power & control system applications. The most common configurations of DCV can be either two or three position valves, controlled by solenoid /mechanical actuated signals. This paper will explain the process for creating efficient mathematical & simulation models of directional control valves that captures the relevant dynamics using Simulink/SimHydraulics software and match the characteristics available in technical literature. The paper also discusses the methods of parametrization of DCV from the available design data. The results of simulations are compared with the characteristics of DCV available in literature. The dynamic step response of DCV found showing stable behaviour during simulation.

Keywords – Direction control valve (DCV), Simhydraulics, simulation, hydraulic system, spool

1.Introduction

Hydraulic systems are widely used in many industrial applications due to their ability to economically convert mechanical energy to fluid energy. It is regulated to provide force, speed and direction of control with the help of arrangement of simple components. It is used in construction, defence, aircraft, manufacturing and mining industries due to their higher power to weight ratio as compared to electrical and pneumatic power transmissions systems.

The hydraulic system includes nonlinearities in static and dynamic characteristics of their components and sometimes show undesirable behaviour. The source of nonlinearity is often due to backlash, friction, and on-off switches whose behaviour is not well modeled.

One of the most important considerations in design of any hydraulic system is control system. The components of control are required to be very precisely selected so as to perform the intended function. These controlling elements are called valves and these are generally three types namely direction control valves, pressure control valves (PCV) and flow control valves (FCV). The scope of this paper is limited to directional control valves only.

Many researchers deal with modeling and control of hydraulic systems. Kishor and Rajsekhar

[1] presented the performance of spool type directional control valve with cylinder and developed the Simulink models. Valery and Steve [2] performed parametrization of DCV's in SimHydraulics. They modeled the power stage and valve actuator from technical information of manufacturer. Liang Li et al [3] constructed mathematical model and fuzzy logic algorithm for PID control of erecting system. Patil and Sondur [4] carried out mathematical modeling and simulation of direct acting pressure relief valve and presented the Simulink dynamics models with compressibility effects. Sondre et al [5] carried out the black box modeling and system identification mobile proportional valves and performed the frequency response analysis. Wladyslaw and Jaroslaw [6] developed mathematical model of hydraulic valve and presented the computer model in Simulink environment. Sulk and Jan [7] performed the nonlinear modeling of spool valve with fuzzy logic and PIC controllers. They have also considered the effects of static, coulomb and viscous friction forces. Wei and Chaoyu [8] investigated the reversing operation of pilot check valve and carried out simulation and experiments. The authors concluded that the response becomes faster with smaller spool diameter.

Michael [9] presented full and reduced order model of hydraulic cylinder. He addressed the dynamic

properties of models, with focus on frequency response, system damping and state trajectories related to load pressure. Dechrit and Nitin [10] presented the modeling of nonlinear hydraulic servo system (HSS). They developed closed loop mathematical models and concluded that HSS can provide higher speed of response. Sudhakar and Madhvan [11] performed the dynamic analysis of closed loop hydraulic system with custom made 5/3 directional control valve. They analysed the closed loop hydraulic system and discussed total pressure control using PID controller.

2. Description of direction control valve

The schematic diagram & cut section of spool type DCV are shown in Figure 1. The inlet port of valve is connected to the pump which draws hydraulic fluid from the reservoir and thus provides inlet flow and pressure. The outlet port is connected to the hydraulic actuator (cylinder/motor) to deliver the working flow and return port is connected to the reservoir / tank allowing the return flow back to the tank.

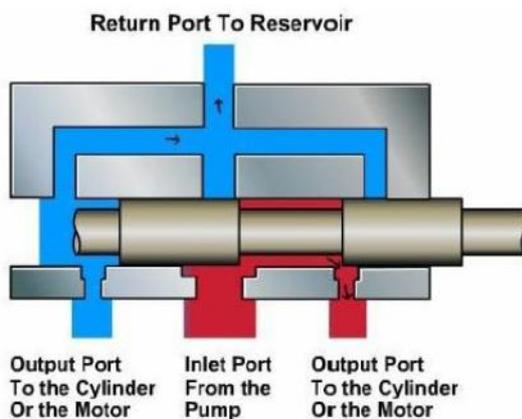


Figure 1 – Schematic of DCV

Any valve contains ports that are external openings through which a fluid can enter and exit via connecting pipelines. The number of ports on a DCV is identified using the term “way.” Thus, a valve with four ports is a four-way valve. A DCV consists of a valve body or valve housing and a valve mechanism usually mounted on a sub-plate. The ports of a sub-plate are threaded to hold the tube fittings which connect the valve to the fluid conductor lines.

3. Mathematical Modeling

The schematic representation of control valve and actuator is shown in Figure 2. It consists

of a double-acting hydraulic piston. The cylinder ports are connected to a direction control valve, and piston motion is obtained by modulating the oil flow into and out of the cylinder chambers. The actuator can be precisely controlled by regulating the flow rates Q_1 and Q_2 given by following equations [11]: -.

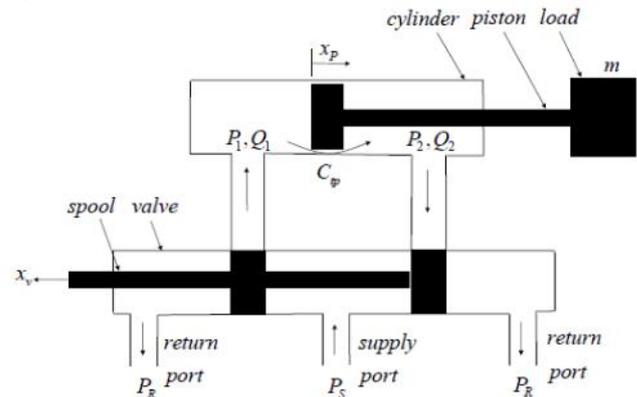


Figure 2. A Hydraulic actuator with 4-way valve configuration

$$Q_1 = C_d A x_v s \quad (P_3 - P_1) \sqrt{\frac{2}{\rho} |P_3 - P_1|}, \quad x_v > 0 \quad (1)$$

$$Q_1 = C_d A x_v \frac{2}{\rho} P_1, \quad x_v < 0 \quad (2)$$

$$Q_2 = -C_d A x_v s \quad (P_3 - P_2) \sqrt{\frac{2}{\rho} |P_3 - P_2|}, \quad x_v < 0 \quad (3)$$

$$Q_2 = C_d A x_v \frac{2}{\rho} P_2, \quad x_v > 0 \quad (4)$$

The following sgn(x) function is used

$$s(x) = \begin{cases} 1 & \text{if } x_v > 0 \\ 0 & \text{if } x_v = 0 \\ -1 & \text{if } x_v < 0 \end{cases} \quad (5)$$

The dynamics of the direction control valve follows linear differential equation of second order and is represented by following equation: -

$$m \frac{d^2 x_v(t)}{d^2} + c \frac{dx_v(t)}{d} + k x_v(t) = F \quad (6)$$

By substituting $k = m\omega_n^2$ and $c = 2\zeta\sqrt{k}$ in equation(6) we get,

$$\frac{d^2 x_v(t)}{d^2} + 2\zeta\omega_n \frac{dx_v(t)}{d} + \omega_n^2 x_v(t) = \omega_n^2 u(t) \quad (7)$$

The system behaviour is described by two fundamental parameters, natural frequency

$$\omega_n^2 = \sqrt{\frac{1}{I^2} + \omega_d^2} \quad (8)$$

and its damping ratio

$$\zeta = \frac{1}{\sqrt{1 + \tau^2 \omega_d^2}} \quad (9)$$

With the initial conditions being $x_v(0) = 0$, $\dot{x}_v(0) = 0$ and $u(0) = 0$, we can apply the Laplace transform to equation (7) which results in

$$s^2 X(s) + 2\omega_n \zeta s X(s) + \omega_n^2 X(s) = \omega_n^2 U(s) \quad (10)$$

Hence transfer function can be evaluated as

$$G(s) = \frac{X(s)}{U(s)} = \frac{\omega_n^2}{s^2 + 2\omega_n \zeta s + \omega_n^2} \quad (11)$$

On further rearranging equation (11) transfer function can be expressed as

$$G(s) = \frac{X(s)}{U(s)} = \frac{1}{\frac{1}{\omega_n^2} + \frac{2\zeta}{\omega_n} s + 1} \quad (12)$$

The system behaviour can now be described by the poles, namely if the denominator of the transfer function set to zero. From the equation (9) we obtain $S_1 = \omega_n(-\zeta \pm \sqrt{\zeta^2 - 1})$, which gives us three possible states for the spool behaviour, dependent on value of ζ . Generally, the damping ratio is less than one ($\zeta < 1$) and hence we find two complex values for s . The system is under-damped and oscillates with the damped frequency $\omega_d = \omega_n(\sqrt{1 - \zeta^2})$

On applying the continuity equation to the fluid flowing in each chambers of hydraulic cylinder, the following equations are derived.

$$Q_1 = A_1 \frac{dx_p}{dt} + C_{ti} (P_1 - P_2) + \frac{V_1}{\beta} \frac{dP_1}{dt} \quad (13)$$

$$Q_2 = A_2 \frac{dx_p}{dt} + C_{ti} (P_1 - P_2) - C_{to} P_2 - \frac{V_2}{\beta} \frac{dP_2}{dt} \quad (14)$$

4 Modeling of DCV in Simulink

Simulink is a graphical extension to MATLAB for the modeling and simulation of systems. In Simulink, systems are drawn on screen as block diagrams. Many elements of block diagrams are available, as well as virtual input devices and output devices. Simulink is integrated with MATLAB and data can be easily transferred between the programs.

In Simulink library, most of the blocks needed for modeling basic systems can be found in the subfolders of the main "Simulink" folder. There are two major classes of elements in Simulink, these are blocks and lines. Blocks are used to generate, modify, combine, output, and display signals.

4.1 Static Simulink model developed as per flow equation (1) of direction control valve is shown in Figure 3. The various parameters such as pressures, coefficient of discharge, area of valve orifice, actuating force, simulation time are required to be specified in Matlab workspace to run the simulation.

4.2 Dynamic Simulink model of DCV developed based on linear differential of second order is shown in Figure 4. The values [3] of mass, spring stiffness, damping coefficient & actuating force is specified as: $m = 0.185$ kg, $k = 1.6 \times 10^5$ N/m, $c = 80$ Ns/m and $F = 10$ V for 1 cm spool displacement. A step input is given to estimate the dynamic response.

4.3 Dynamic Simulink model as per equation (7) of directional control valve is shown in Figure 5.

5 Modeling of DCV in SimHydraulics

SimHydraulics provides component libraries for modeling and simulating hydraulic systems. It includes models of hydraulic components, such as pumps, valves, actuators, pipelines, and hydraulic resistances. We can use these components to model fluid power systems. These models can be used to develop control systems and test system-level performance. We can parameterize the models using MATLAB variables and design control systems for hydraulic system in Simulink. We can also add electrical, mechanical, pneumatic, and other components to hydraulic model using Simscape and test them in a single simulation environment.

5.1 Valve model

The model of a directional valve [14] can be divided into two parts: the control device and the power stage. The control device sets the position of the valve's working member (spool, cartridge, poppet, etc.) in the power stage, which controls the flow of hydraulic fluid. Two models of 4 way & 3 way of directional valves represented in Sim - Hydraulics are shown in Figures 6 (a) and (b).

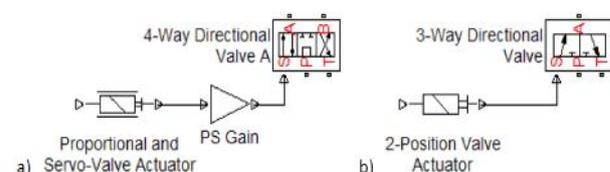


Figure 6 (a) 4 way DCV and (b) 3 way DCV model

The power stage of DCV is modeled using a combination of variable orifices. Figure 7(a) & (b) shows a cross section and schematic for the power stage of considered 4-way directional valve, and the corresponding SimHydraulics model

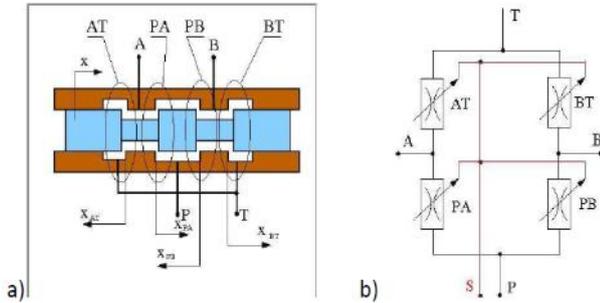


Figure 7 (a) cross section and (b) schematic orifice. The diagram in Figure 7(b) shows four variable orifices named for the ports they connect: variable orifice PA connects the pressure port P and actuator port A, orifice BT connects the actuator port B, return port T, and port S in represents the mechanical translational displacement of the valve spool.

5.2. Valve Parameterization

Every model is characterized by a set of parameters. The parameters specify the model and the process of selecting the set of parameters is referred to as specification [2]. There are following three specification options:

- Option I - By specifying the valve orifice maximum area and opening.
- Option II - By providing a table-specified relationship between the orifice area and its opening.
- Option III - By providing a table-specified relationship between the flow rate, orifice opening and pressure differential.

In this paper, based on the technical data provided in available literature, two different DCV's are modeled by using option I & option III.

The flow rate through the orifice is computed by the equation (1). The key feature of this option I is that the linear relationship exists between the orifice area and opening, which offers higher computational efficiency.

The option I requires three orifice parameters to be determined: orifice maximum area, orifice maximum opening, and orifice initial opening. Flow characteristics of considered EATON/Vickers four-way DCV [12].

Valve parameter values are determined using an optimization procedure in which the required characteristic for the flow rate is compared to the simulation results, and parameter values are adjusted to minimize the difference.

For the analysis and testing the valve, test rig is developed in SimHydraulics is shown in Figure 8. As specified in technical literature of Eaton /Vickers [12], the flow rates are measured in the external valve loop (P-A-B-T) with a pressure drop of 5 bar maintained on each metering path. To maintain the pressure drop of 5 bar across every orifice, ideal hydraulic pressure Source blocks are used to set the pressures at the P, A, and B ports at 10 bar, 5 bar, and 5 bar, respectively.

Further the value [12] of max spool displacement and initial opening found to be 1 cm and -1mm respectively. The only parameter value left to determine is the orifice maximum area. The value of this parameter is considered to be acceptable if the test rig model flow characteristic matches the valve characteristic. The required valve characteristic is defined by 11 points in the 1D lookup table block.

Input signal = 0:0.1:1; % Displacement of valve spool [cm]

Q_r = [0 0 52 150 248 346 450 540 625 670 700];

% Value of corresponding flow rate [l/min]

The control signal generated by the Signal Builder block in the model is shown in Figure 10 which increases linearly from 0 to 1 cm.

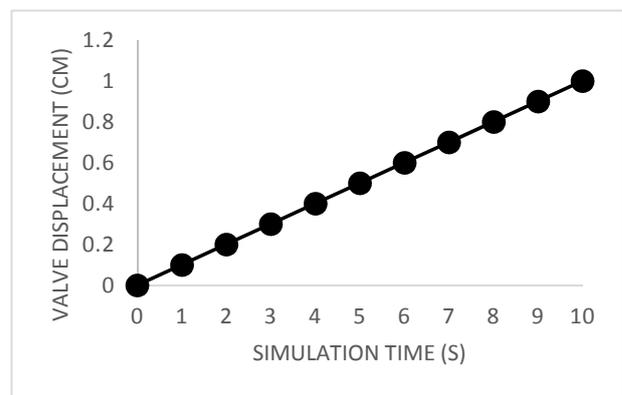


Fig 9 – Control signal to DCV

To obtain 11 flow rate values for comparison with the points extracted from the valve characteristic, the simulation time is set to 10 s and output times are set to generate a solution at 10 intermediate points evenly spread during the simulation.

The objective function [2] for the optimization is defined as given below:

$$\min F(x) = \sum_t \alpha_t (Q_r - Q_a)^2 \quad (11)$$

Modeling of Danfoss proportional DCV PVG 32 [13] has been carried out by specification option III by considering the flow and pressure drop characteristics.

The required flow characteristics and displacement are given below :

Max valve spool displacement = 7 mm

Q_r = [0 0 0 0 3 7 10 15 20 25 33 45 55 70 100];

% Flow rate of valve spool D [l/min]

Pressure drop vs flow characteristics has been used for generation of signal to DCV model. The maximum pressure at maximum flow found to be 45 bar from technical literature [13]. The SimHydraulics test rig prepared in Simhydraulics for modeling of PVG 32 valve is shown in Figure 10.

6. Results & Discussion

(a) Displacement -The simulation result of Simulink model displacement is shown in Figure 11. The maximum displacement value is found to be 1mm.

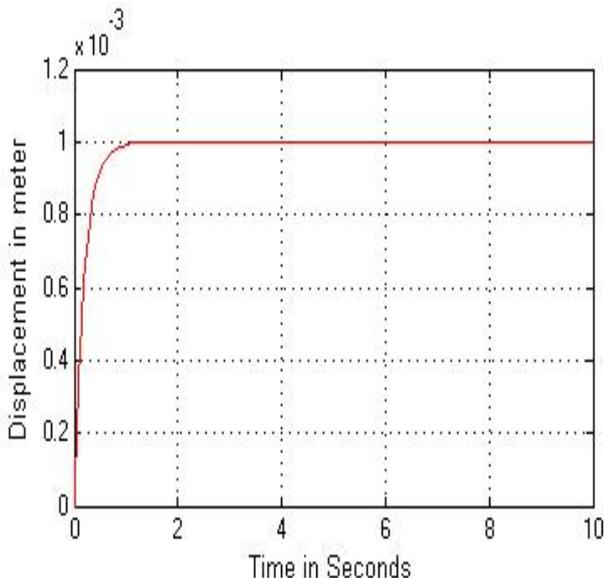


Figure 13 – Displacement vs time plot for dynamic simulink model of DCV, Max value = 1 mm

(b) Velocity - The velocity vs time plot for Simulink model of direction control valve is shown in Figure 12. The maximum value of velocity is found to be 0.004 m/s.

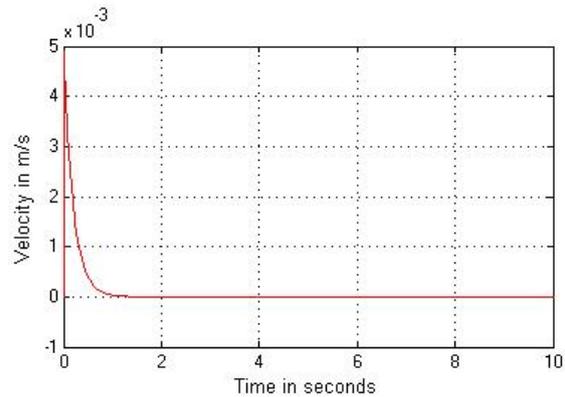


Figure 14 – Velocity vs time plot for dynamic simulink model of DCV, Max value = 0.004 m/s

(c) Characteristics of Eaton / Vickers DCV– The maximum orifice area was optimised with initial guess value of 4.8 cm² and after optimisation its value found to be 5.98 cm². Figure 13 (a) shows comparison of characteristics before optimisation and (b) shows comparison of characteristics after optimisation. It is seen from the plots that the variation of valve & model characteristics are well within 10% .

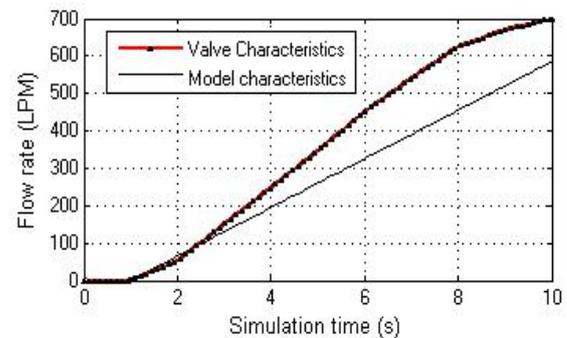


Figure 13 (a) – Comparison of valve and model characteristics before optimisation, variation >10%.

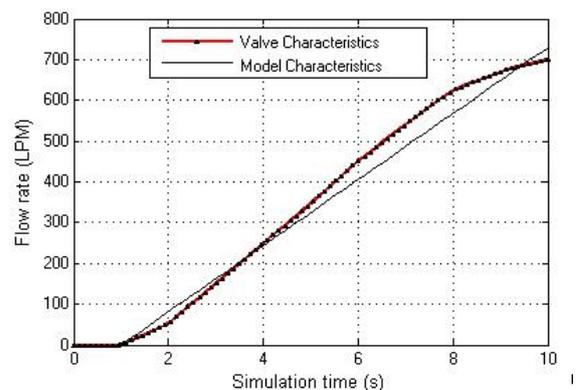


Figure 13 (b) – Comparison of valve and model characteristics after optimisation, variation <10%.

(d) Characteristics of Danfoss Direction Control Valve The simulation results of PVG is shown in Figure 16, shows that the valve & model characteristics are matching within the error of 10 percent. Further the data of 14 points were considered by increasing these points accuracy of simulation improves further.

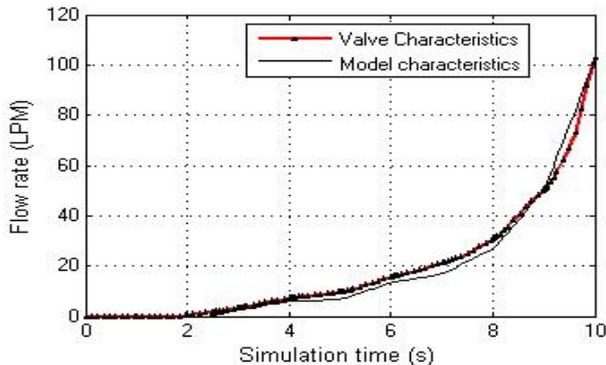


Figure 14 – Comparison of valve and model characteristics variation <10%.

7. Conclusion

The modelling and simulation of the direction control valve systems has been performed using the Matlab Simulink and Simhydraulics and following conclusions are drawn

- The dynamic step response of DCV found showing stable behaviour during simulation
- The response becomes faster with a smaller diameter of the control spool.
- The Simulated model of DCV found matching with valve characteristics and hence can be used for Hydraulic Circuit Simulation
- The use of Simhydraulics for components modeling simplifies design of Hydraulic Circuit , saves time and optimise the system.

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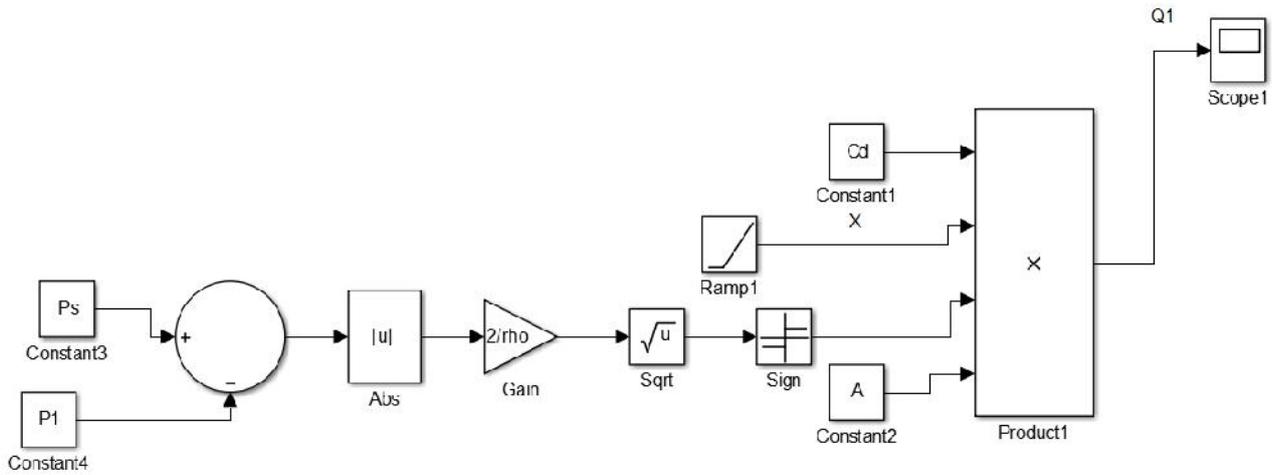


Figure 3 – Static simulink model of Directional Control Valve as per equation (1)

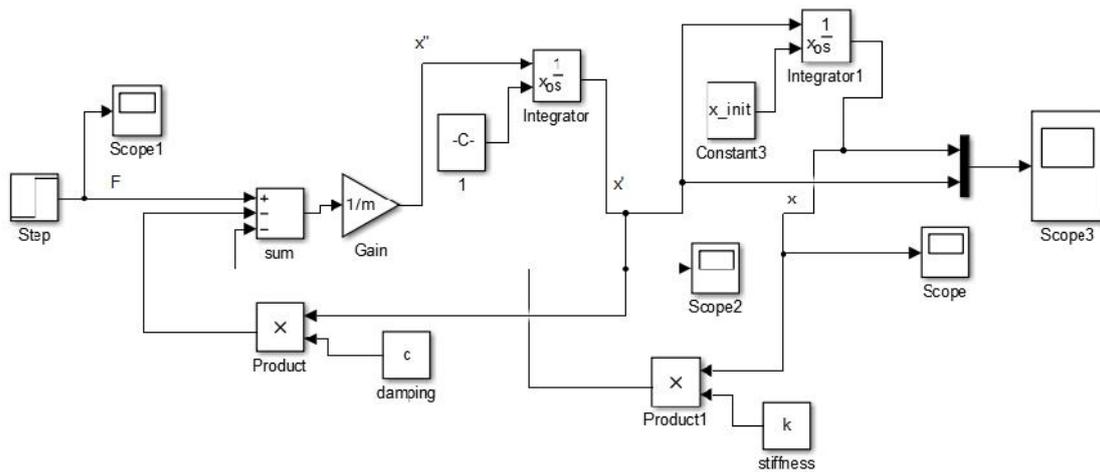


Figure 4 – Dynamic simulink model of Directional Control Valve as per equation (6)

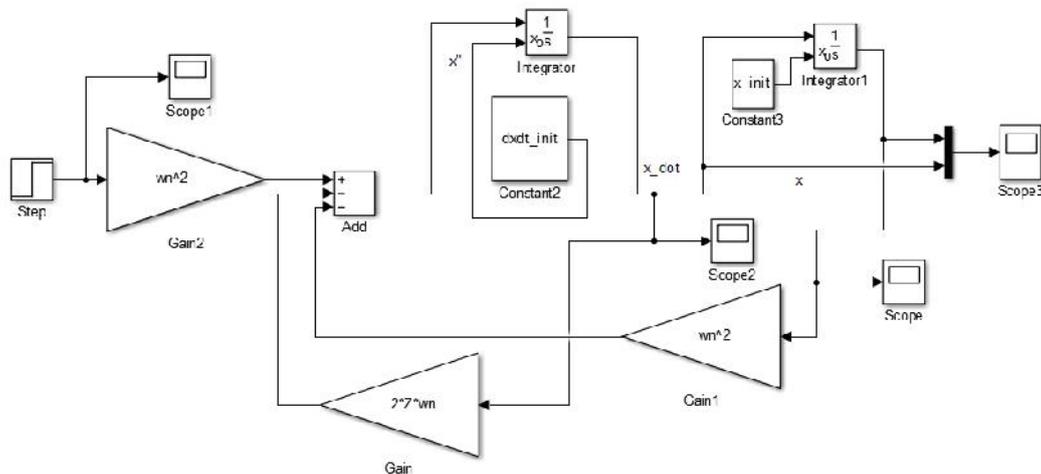


Figure 5 – Dynamic simulink model of Directional Control Valve as per equation (7)

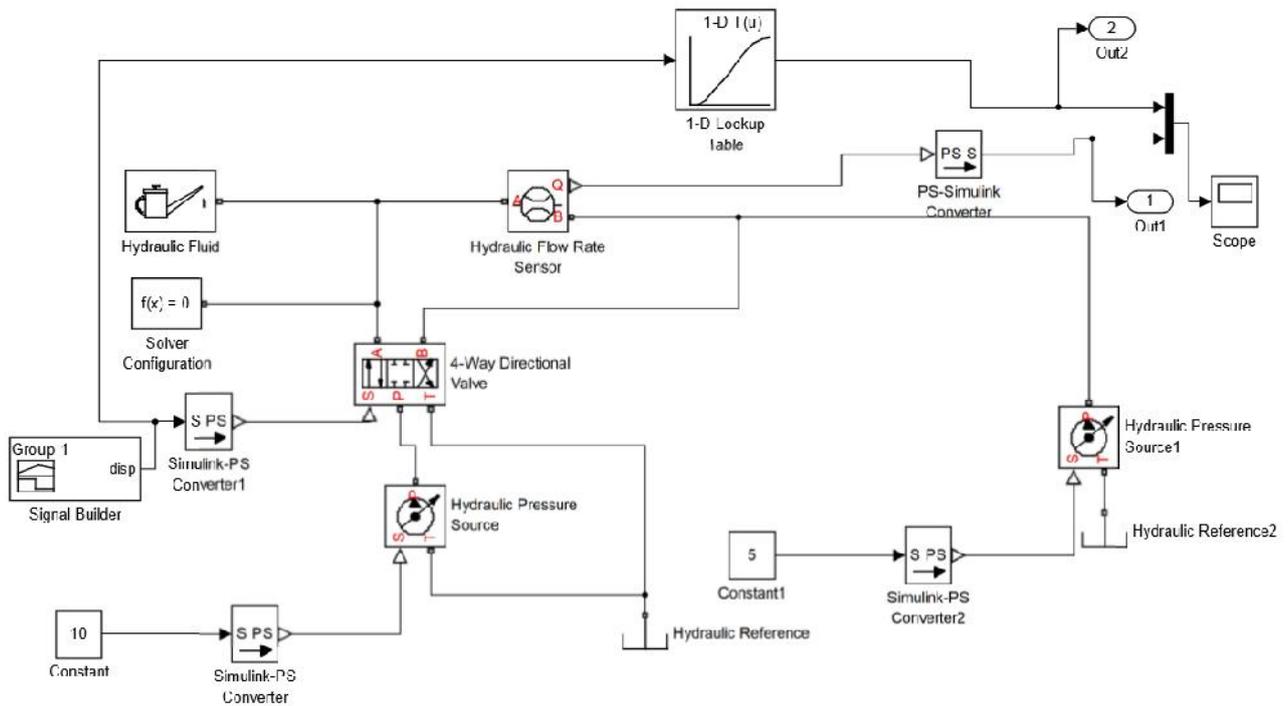


Figure 8 – SimHydraulics model of test rig for simulation of Vickers / Eaton DCV

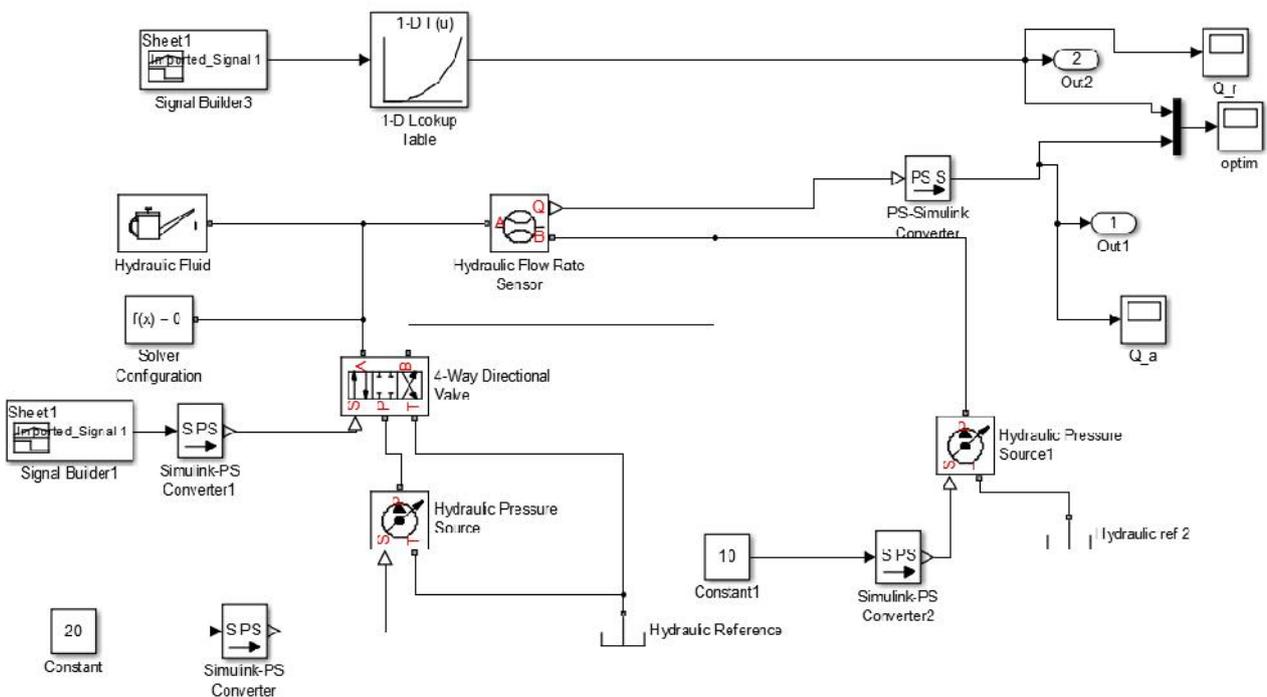


Figure 10 – SimHydraulics model of test rig for simulation of Danfoss DCV