POLITECNICO DI TORINO

MASTER OF SCIENCE IN AUTOMOTIVE ENGINEERING

ENERGY DEPARTMENT
FLUID POWER RESEARCH LABORATORY

COMPARISON OF LUMPED PARAMETER SIMULATION ENVIRONMENTS FOR FLUID POWER APPLICATIONS

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ABSTRACT

This thesis aims at comparing two simulation softwares used for hydraulic circuit simulations. The softwares under study are Simcenter Amesim by Siemens and Simscape Fluids by Simulink. This comparison will reveal itself important in showing how effective a simulation environment like Simulink which is cheaper and more accessible could be in simulating complex automotive hydraulic circuits with respect to a more professional and expensive hydraulic simulation environment as Amesim.

This comparison is done on three hydraulic circuits which are:

- **Vehicle power steering unit hydraulic system.**
- **Hydrostatic transmission for vehicles.**
- **Hydraulic systems for controlling a semi-automatic gearbox.**

The work will start from already built Amesim models of each circuit then circuits of the same characteristics is reproduced on Simscape Fluids and a critical comparison of the results obtained on both platforms is done.

Chapter 1

INTRODUCTION

1.1 Simscape Fluids

Simscape Fluids is a specific library of Matlab Simulink used for simulation of hydraulic circuits. It contains components used to construct the desired hydraulic circuits. It also contains mechanical components that enable hydro-mechanical connections used in creating some circuits. It has a crucial advantage of having an affordable license and easily accessible.

1.2 Simcenter Amesim

Amesim on the other hand is a more professional simulation software used not only for hydraulic circuit simulations but contains diversified detailed libraries this makes its use extendable to a wide variety of engineering fields. The main drawback of this platform is that it is not accessible, and its license is not very affordable. This limits its application to companies or schools not having the ability of purchasing the licenses.

Chapter 2

DESCRIPTION OF SYSTEMS UNDER STUDY

A brief description of the working principles of the systems under study is done to better understand the way layouts used on the various simulation platforms.

2.1 Description Of Vehicle Power Steering Units

Vehicle power steering is a mechanism used by most vehicles to reduce the effort required by the driver during steering manoeuvres. Steering assisting mechanisms can be electrical or Hydraulic. The mechanism described in this section is the hydraulic assisted steering.

The Hydraulic power steering consists of hydro-mechanical components such as Steering Wheel, Steering Column, Torsion bar, Spool-Sleeve mechanism, Pump, a Rack and Pinion coupling.

Figure 2-1 - steering wheel

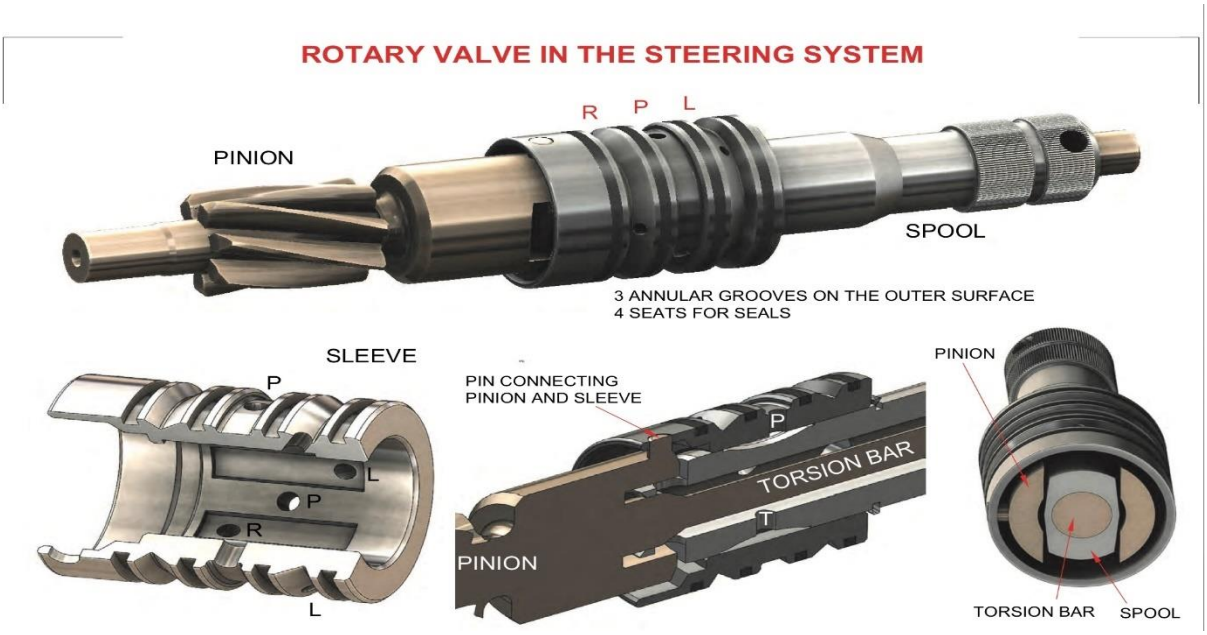


Figure 2-2 - Spool Sleeve Assembly [2]

The above figures show the steering wheel and spool sleeve assembly which are fundamental components for the working of the power steering unit. The steering wheel is connected to the torsion bar which has a small torsional stiffness (The effort by the driver on the steering wheel will be that needed to twist the torsion bar) via a steering column which in turn is connected to the spool. The sleeve and spool constitute a bridge (due to the overlap/underlap area variations caused by spool-sleeve relative rotation) which regulates the passage of hydraulic fluid from the pump to the double acting cylinder which causes motion of the rack.

The rack motion causes a rotation of the pinion which balances the bridge (negative feedback mechanism) since it is rigidly connected to the sleeve.

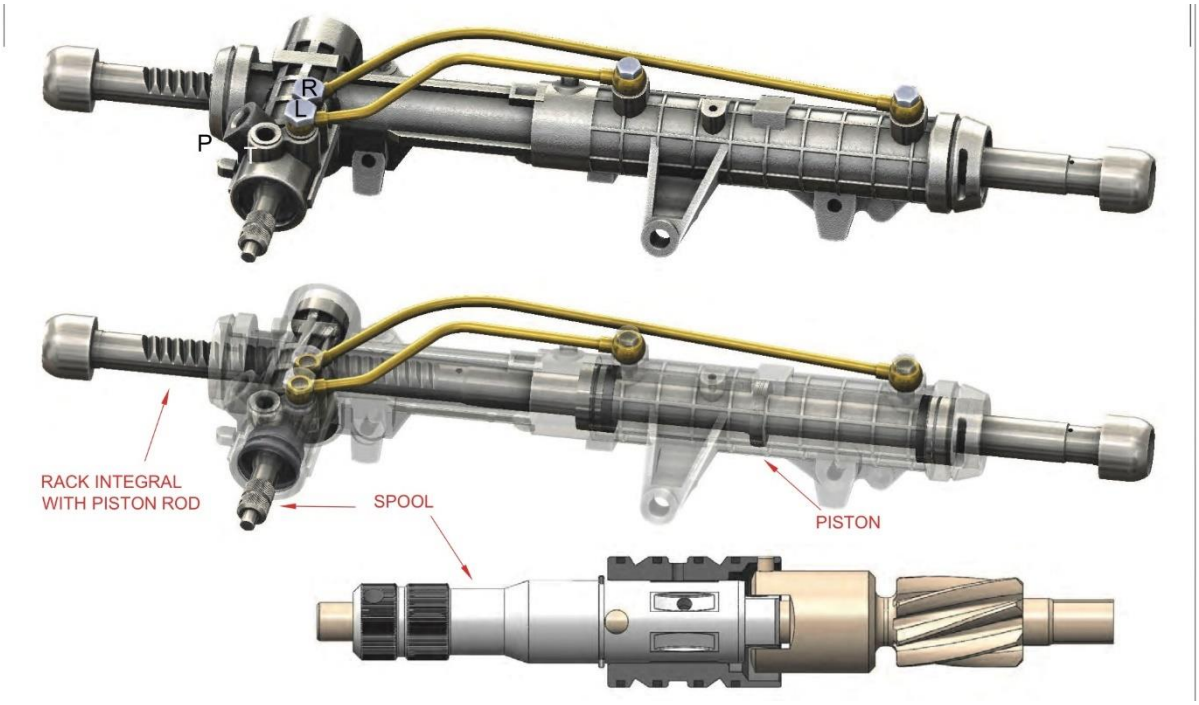


Figure 2-3 - Rack and Pinion connected to double acting cylinder [2]

However, the steering mechanism should be able to work even in absence of the hydraulic assistance due to a potential failure of the hydraulic circuit. This is done by the presence of a hard stops which limit the relative rotation between spool and sleeve (usually +/- 8 to 9 degrees) and in this position the torque from the steering wheel is directly applied to the pinion which then causes the rack to translate. But this requires a larger amount of effort from the driver.

Another particularly key component of this system is the flow control mechanism which limits the amount of flow reaching the double acting cylinders and avoids over sensitivity of the steering system i.e., a large steering speed of the wheel corresponding to a small steering angle of the steering wheel at high engine speeds. This is usually because the flow rate from the pump is proportional to its rotational speed which in turn is directly coupled to the engine speed. Hence at high engine speed the flow rate from the pump increases and the flow rate reaching the double acting actuators is high and this causes a high translation velocity of the actuator.

A pressure relief valve is also necessary for safety reasons to limit the pressure in the hydraulic circuit to a maximum value which corresponds to the valve setting.

The figure below shows a representation of a complete power steering system with the various components drawn according to the ISO 1219/1-91 standards.

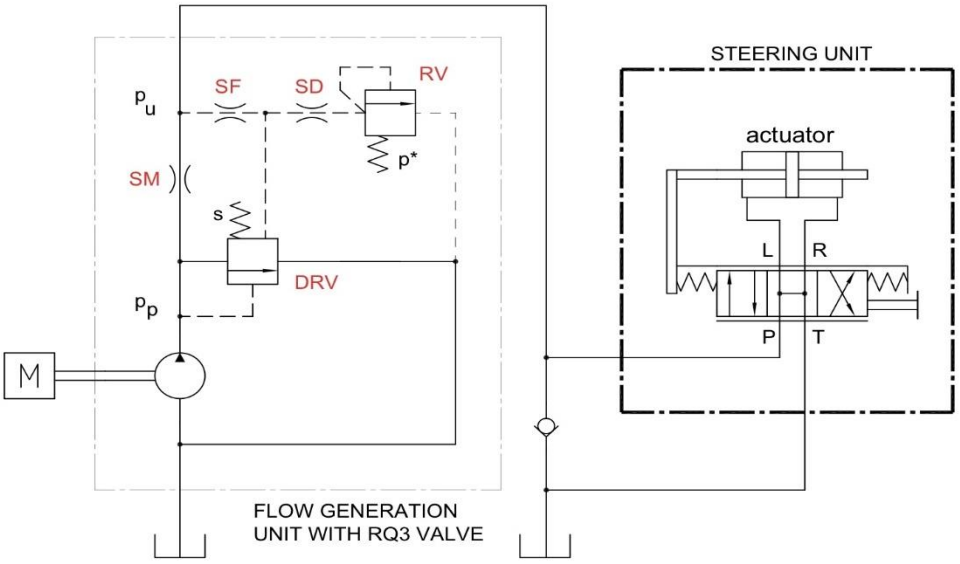


Figure 2-4 – Power steering system layout according to ISO-1219 [2]

Several types of pumps can be used in power steering systems. The figure below shows a balanced rotor vane pump with a flow control and pressure relief integrated in the block.

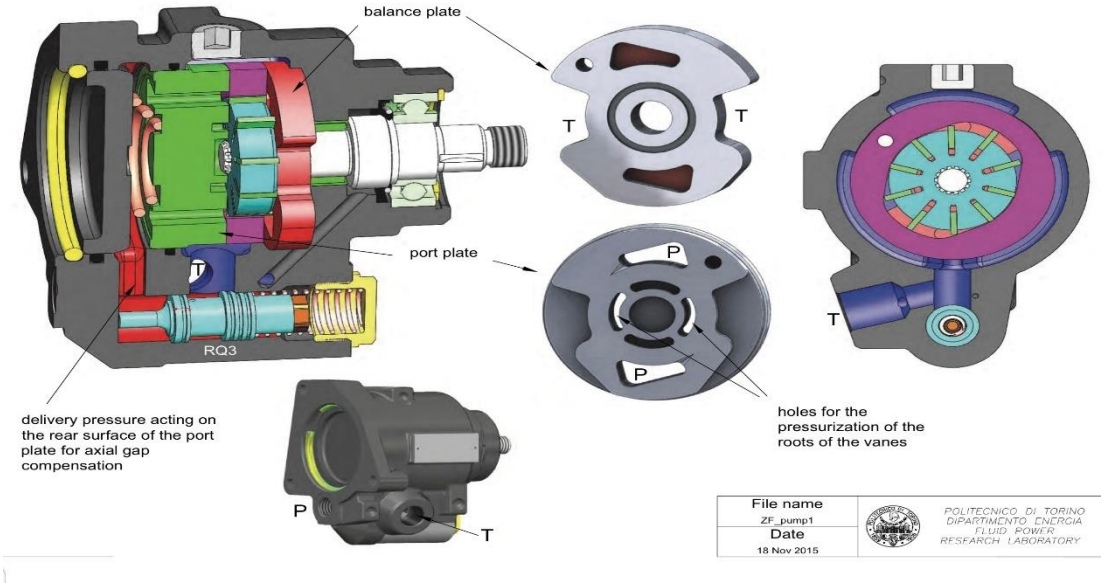


Figure 2-5 - Balanced rotor vane pump for automotive steering [2]

2.2 Description Of Hydrostatic Transmissions For Vehicles

Hydrostatic transmissions for vehicles are close circuits that use hydraulic fluid as medium of power transfer from engine to wheel. They are advantageous because of their compactness and low transmission efficiencies.

They have 4 characteristic working modes as shown in the diagram below.

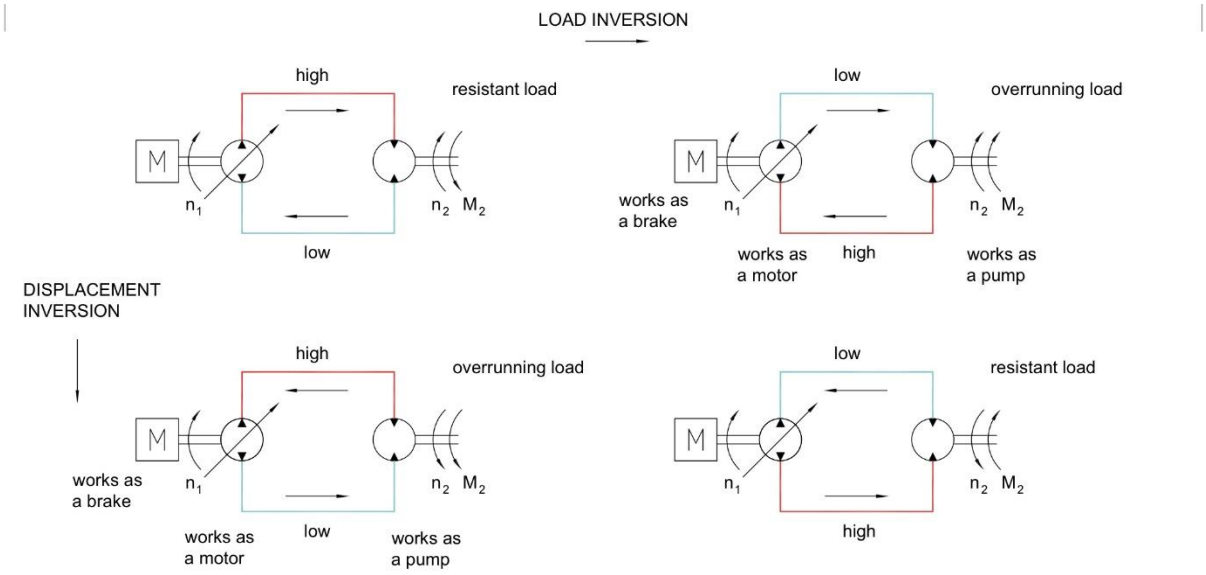


Figure 2-6 - Hydrostatic transmission working modes [2]

These working modes are Forward acceleration, Forward deceleration, Reverse deceleration, Reverse acceleration. These working modes can be plotted on a speed-torque plane on which the limit curves indicating the operational domain can be seen as shown below.

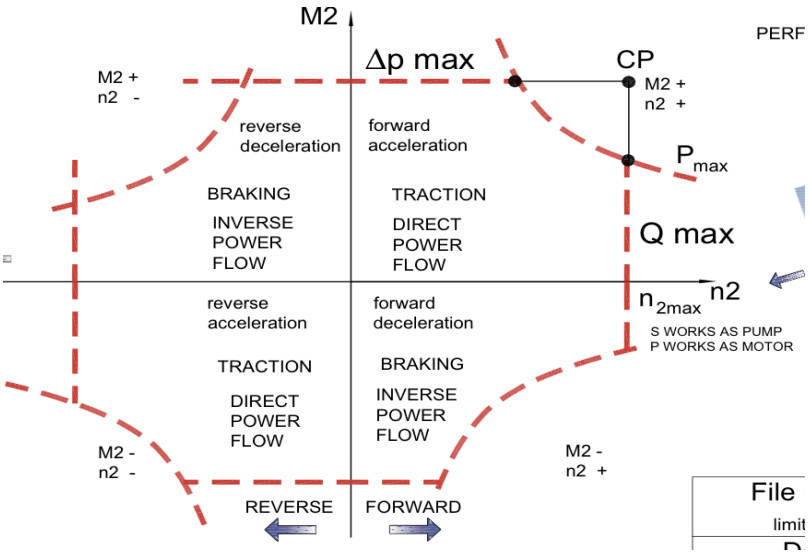


Figure 2-7 - Speed - Torque operational domain of hydrostatic transmissions [2]

The main characteristic variables of the hydrostatic transmissions are.

- **Transmission ratio $\nu = n_2/n_1$** where n_1 and n_2 are the pump and motor speeds respectively.
- **Torque ratio $\tau = M_2/M_1$** where M_1 and M_2 are the pump and motor torque respectively.

As shown on the figures above, the hydrostatic transmissions are made of a high-pressure (represented in red) and low-pressure lines (represented in blue). This brings about certain problems to be solved in order to have a proper functioning of the hydrostatic transmission. These problems are.

- Defining the pressure on the low-pressure line and this solved by a pressure relief valve always connected to the low-pressure line.
- Limiting the pressure on the high-pressure side done by a pressure relief valve connected to the high-pressure line.
- Providing a flow rate to the circuit to compensate for the external leakages and this is done by a charge pump providing an extra flow to the circuit.
- It is necessary to control the temperature and oil contamination, and this is done by a conditioning system.

Note that the pressure relief valves are always double I.e., one relief valve is placed on each line, and this is because the system is reversible.

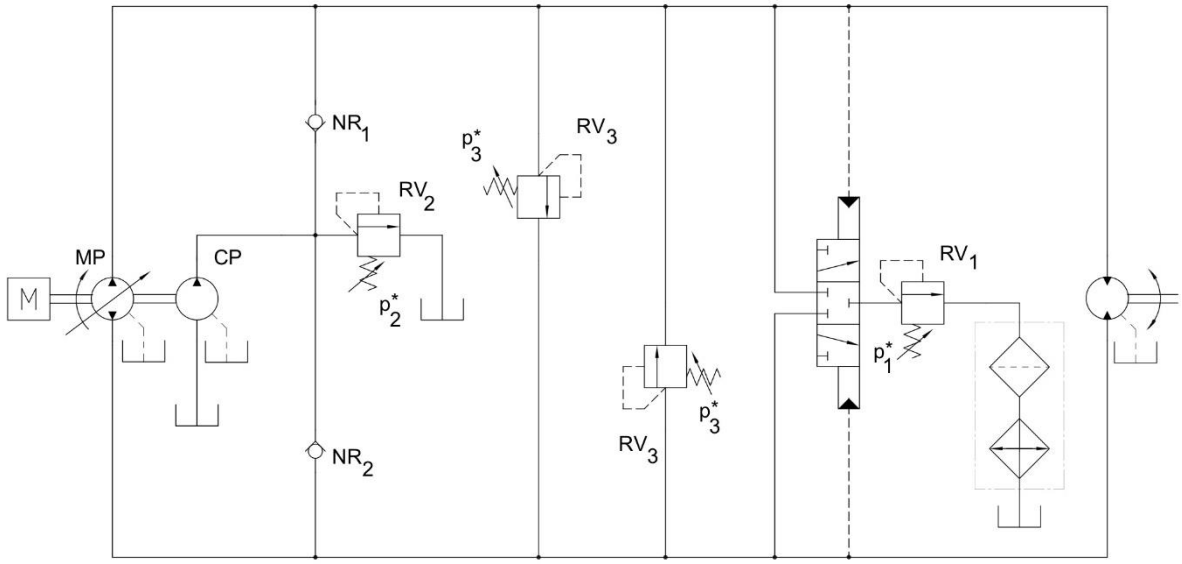


Figure 2-8 - Closed circuit hydrostatic transmission with pressure relief valves

- RV_1 is the low-pressure relief valve.
- RV_2 is the safety valve.
- RV_3 is the high-pressure relief valve.

The circuit under study in our case double motor hydrostatic transmission which is made of one variable displacement pump and two variable displacement motors. The advantage of this layout is the possibility of increasing considerably the output speed and hence the **Torque Conversion Ratio** abbreviated **TCR**[1] by varying adequately the displacements of the pump and motors.

[1] Defined as the ratio between the maximum and minimum speeds of the output shaft $TCR = n_{2max}/n_{2min}$.

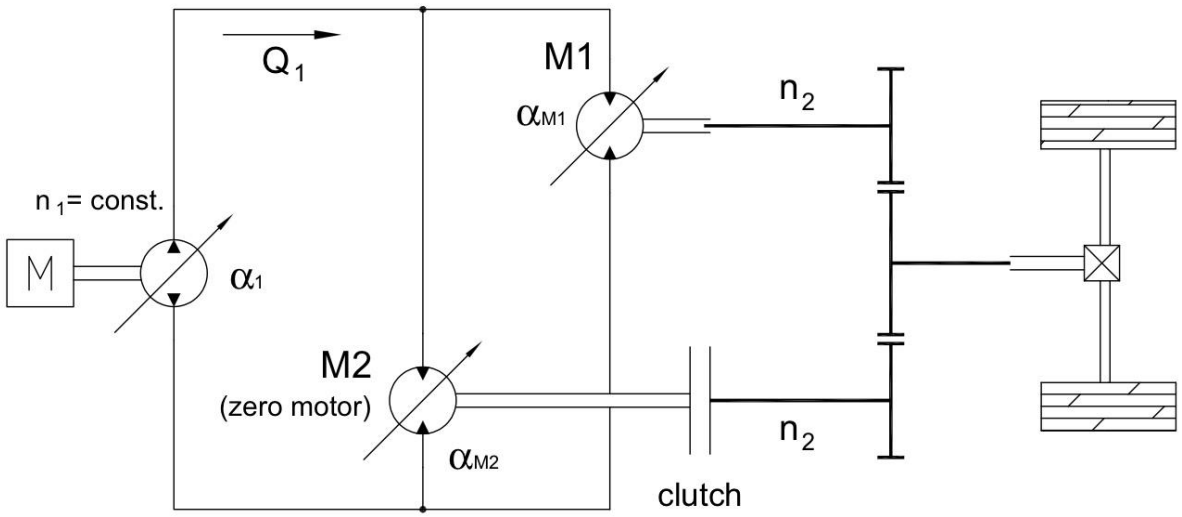


Figure 2-9 - PV-SV multi motor transmission

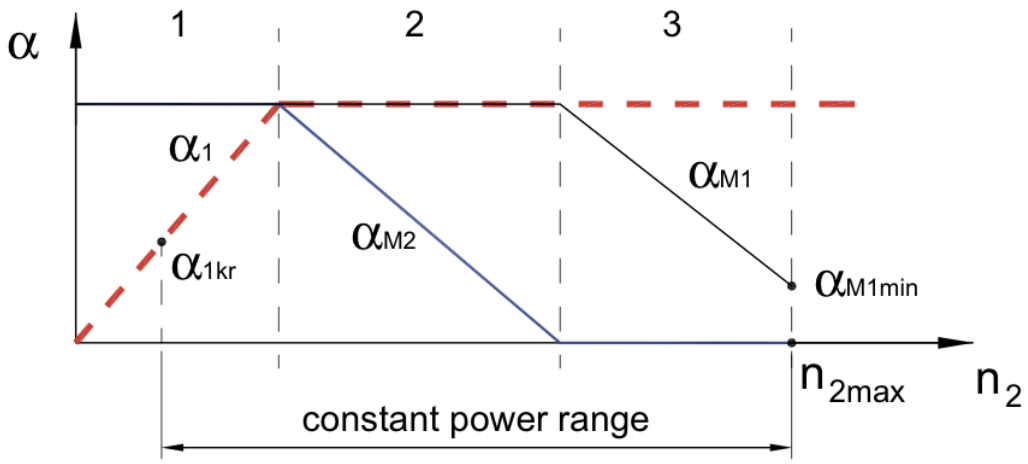


Figure 2-10 – Displacement variation sequence of pump and motors

2.3 Description Of Hydraulic Systems For Controlling A Semi-Automatic Gearbox

The system studied is an electro-hydraulic system (Selespeed ®) for gear selection and engagement. This system is applied on vehicles substituting the conventional manual lever. It also carries out the function of engaging and disengaging the clutch to optimize the performance during the gear changing phase hence higher traction to the vehicle.

The figure below is the graphical representation of the circuit of the Selespeed electro-hydraulic system.

An approximately fixed pressure flow generating unit delivers flow to a high-pressure line (between 37 and 55 bar), from which power is drawn to enable the functioning of all the actuators. The flow generation group Is made of a pump (gerotor) which works intermittently since it is commanded by a pressure switch. The pressure switch turns on the motor when the pressure on the line drops below 37bar and turns off the motor when the pressure on the line rises above 55bar. The accumulator stores fluid with the aim of increasing the intermittence time of the pump. In case of failure, a relief valve avoids the line pressure go rise above 82 bar.

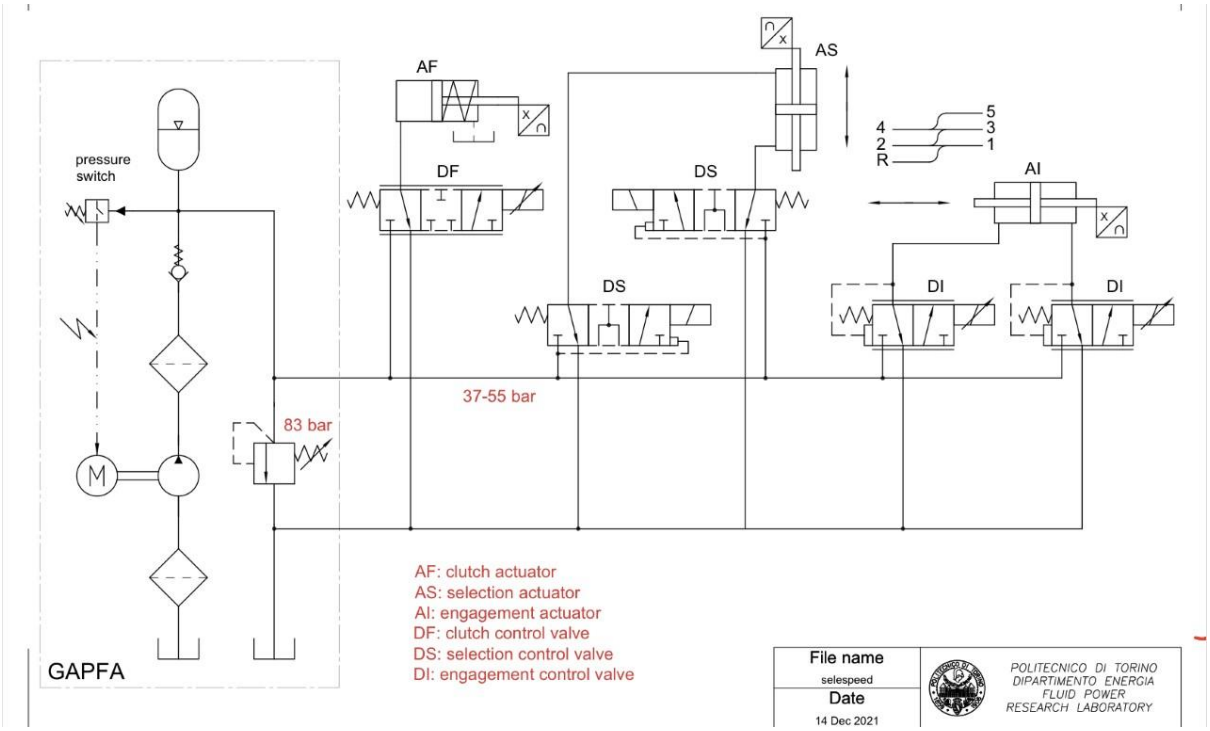


Figure 2-11 - Selespeed system circuit

- The directional flow control valve commands the actuator AF which on its turn acts directly on the clutch spring.
- The directional flow control valves DI command the actuator AI which enables the engagement and disengagement of gears.

- The directional control valve DS commands the actuator AS which enables the selection of gears.

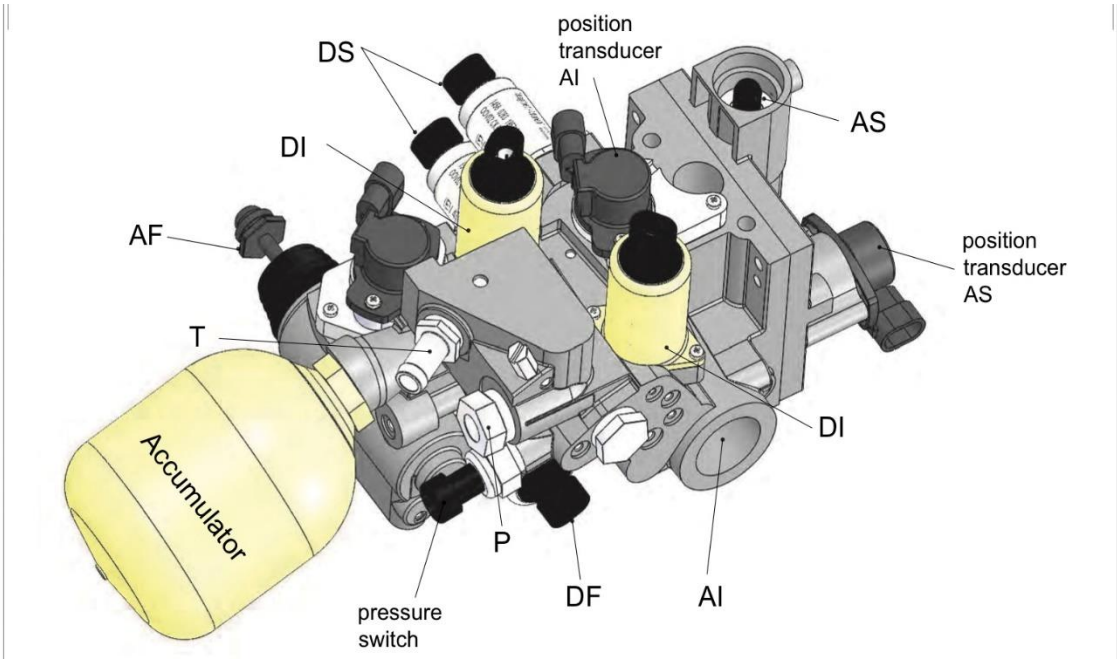


Figure 2-12 - CAD 3D model of Selespeed module

Chapter 3

AMESIM MODEL DESCRIPTION OF SYSTEMS UNDER ANALYSIS

In this section, a brief explanation of the construction of the various models i.e., the description of each component and the various parameters imposed on them on Amesim is done and the various characteristic plots is described. As said in previous sections, the study of these systems starts from already built Amesim models with the various characteristic curves already plotted.

3.1 Amesim Model Description Of A Power Steering Unit

The Amesim model of the power steering unit has two distinctive parts which are, **A mechanical assembly** and **A hydraulic circuit** which are interconnected with each other through the spool-sleeve mechanism.

The mechanical assembly starts from the steering wheel where the driver gives an input signal. This signal corresponds to a steering wheel angle and this angle is transferred through the steering column (with a high stiffness **K = 202.75 Nm/degree** represented by a rotational spring and a rotational inertia **J = (6.61048e-06) *11 kgm^2** and **viscous damping coefficient** of **0.003 Nm/(rev/s)** represented on the cylinder-shaped block) to the torsion bar.

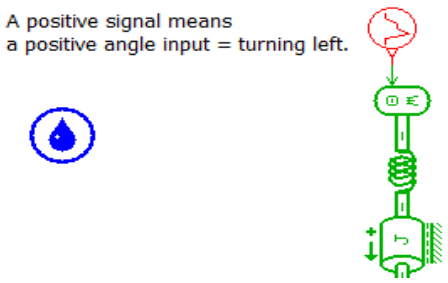


Figure 3-1 – Steering wheel - steering column connection

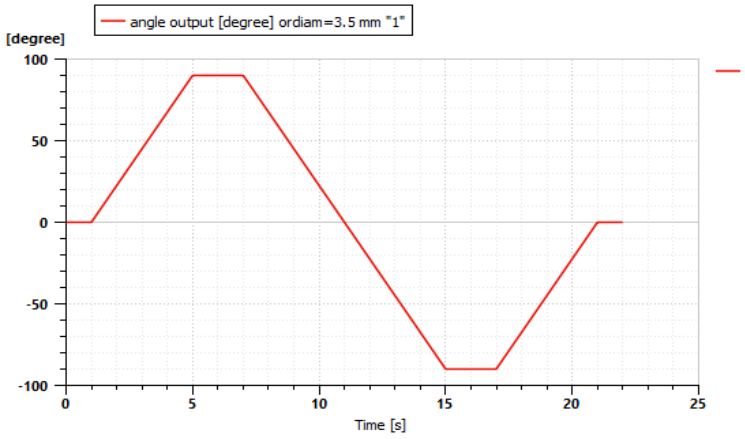


Figure 3-2 - steering input signal

The rotation of the steering column causes the rotation on the spool to which it is connected by a pin relative to the sleeve and varies the passage area of hydraulic fluid between the spool and the sleeve. This mechanism is represented on Amesim as shown below.

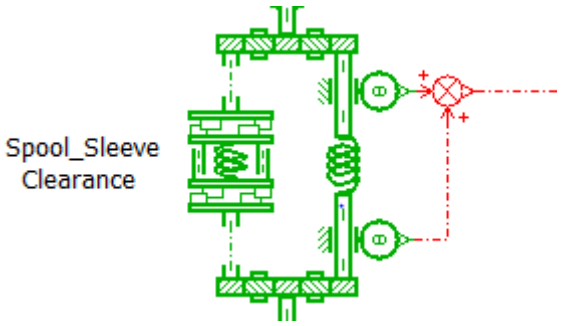


Figure 3-3 - Spool-Sleeve relative rotation and hard stop parameters

The rotational spring on Figure 3-4 above represents the torsional bar stiffness **K = 1.227Nm/degree** and a component that simulates the maximum relative rotation between the spool and sleeve which is **+/- 7 degrees.** It should be noted the presence of two sensors that measure the relative position the sleeve and spool and as it will be shown later associates a valve area opening and hence the amount of flow reaching the actuator.

The sleeve is linked to the pinion of radius **10.36mm** which is modelled considering its stiffness **K = 2277.9Nm/degree** which is represented by a rotational spring and an inertia **J = 3.12245e-05 kgm^2** represented by a cylinder-shaped component with **viscous friction coefficient 0.01 Nm/(rev/s).** The figure below shows the rack and pinion assembly.

Figure 3-5 - sleeve pinion and rack assembly

The translation dynamics of the rack is represented by a **mass of 3.44kg** and a **viscous friction coefficient of 10000 N/(m/s)** with displacement which goes from **+0.0825mm to -0.0825mm.** An external load is applied to the system using a spring with stiffness **K = 200000N/m** which simulates an external force. The rack is rigidly connected to the double acting hydraulic actuator. This translational assembly is shown below.

Figure 3-6 - Translational assembly of steering system on Amesim

The hydraulic part of the assembly starts with the pump with a **displacement of 8.5cc/rev** with an input signal which describes the speed profile of the pump during the simulation as shown below.

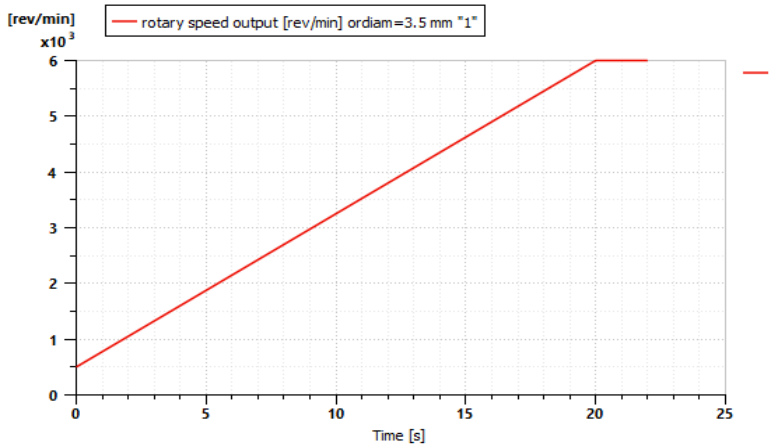


Figure 3-7 - speed profile of fixed displacement pump

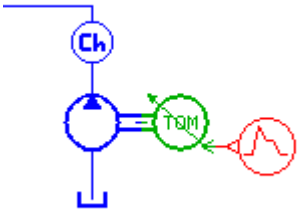


Figure 3-8 - fixed displacement pump

As said above the **flow control valve RQ3** needed to control the flow rate reaching the actuator is modelled as shown below.

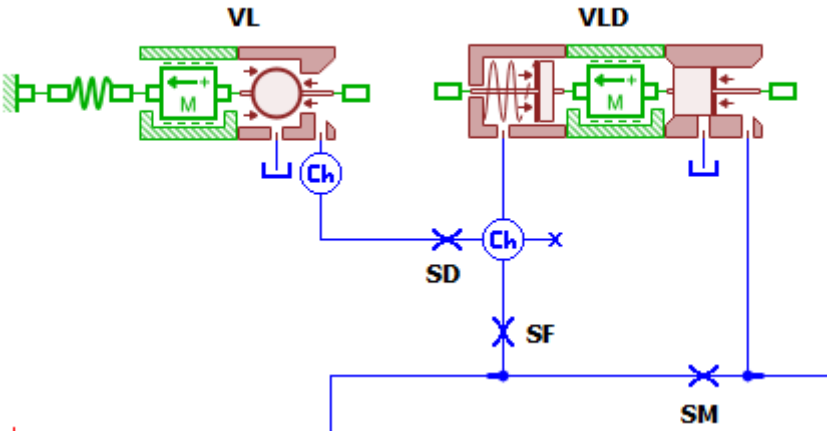


Figure 3-9 - RQ3 flow control valve

The RQ3 flow control valve constitutes of a **metering restrictor SM** which due to its restriction area of diameter **d = 3.5mm**. The pressure drop across the metering restrictor is imposed by the pressure setting of the **VLD** whose pressure setting is given by a spring with stiffness **K = 1N/mm** acting on a spool of diameter **d = 17mm** and the spring preload force is of $\mathbf{F_0 = 38N.}$

The valve **VL** is a pressure relief valve that limits the pressure in the entire circuit to a given value in case the pressure in the circuit rises uncontrollably. It is a small valve in this case since only a small flow rate passes through it during its regulation. The pressure valve setting is done using a spring with

stiffness **K = 27000N/m** acting on a ball poppet of mass **m = 0.0025kg** and diameter **d = 4.48mm** and seat diameter **d = 3.35mm.**

The dynamic restrictor **SD** due to its restriction area controls the oscillations during the opening and closing of the pressure relief valve due to its restriction area.

The flow then reaches a 4-port 3-position directional control valve which is physically represented by the spool-sleeve assembly and whose functioning is like that of a **Graetz bridge.** The relative angle between spool and sleeve is used as an input signal which is then interpolated using a text file with associates the relative angle to a passage area of the fluid to the actuator. This causes an increase in pressure on one side of the actuator and a decrease on the other.

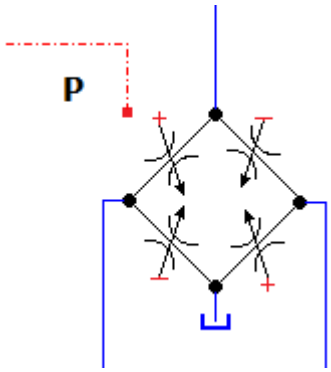


Figure 3-10 - directional flow control valve to the double acting actuator

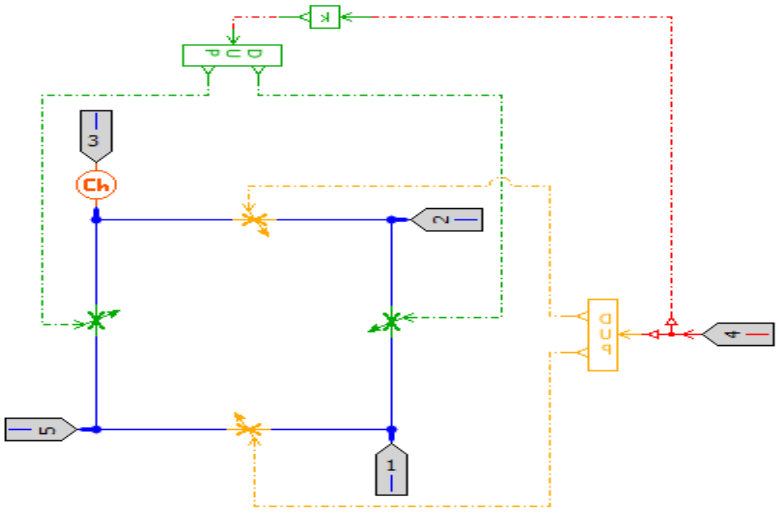


Figure 3-11 - detailed layout of the directional valve.

The fluid then reaches a double acting actuator made of a piston of diameter **d = 38mm** and two identical rods on both sides of diameter **d = 23mm.** The piston from its rest position can move left and right with a 0.0825 maximum displacement and this displacement is caused by the pressure unbalance on both sides of the piston.

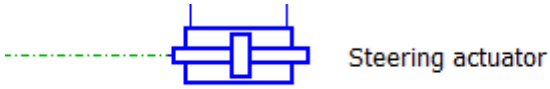


Figure 3-12 - double acting hydraulic actuator

The complete steering system on Amesim is shown on the next figure.

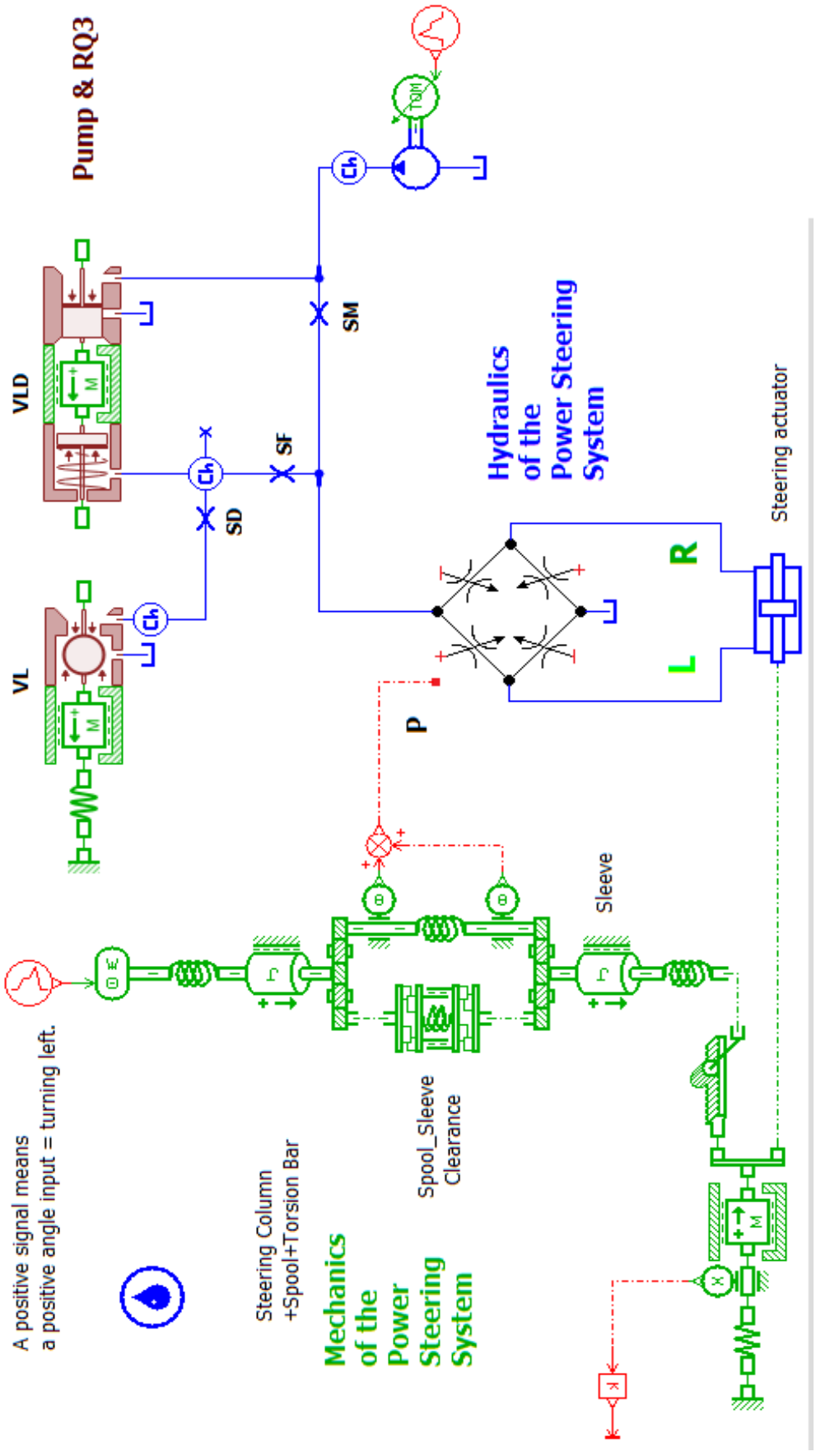


Figure 3-13 - complete Amesim model of power steering unit

3.2 Amesim Model Description Of The Hydrostatic Transmission

This section shows the layout of the double motor hydrostatic transmission on Amesim.

A Prime mover rotating at **1400rpm** drives the charge pump which is a fixed displacement pump with a displacement of **15cc/rev** and a variable displacement pump of maximum displacement **75cc/rev.**

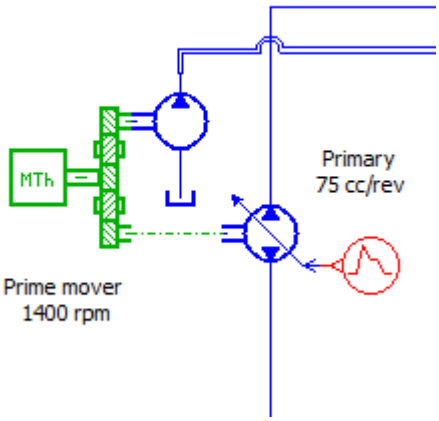


Figure 3-14 - Prime mover connected to both pumps

The charge pump is connected to a relief valve that is always regulating and has a pressure setting of **25bar.** Two check valves that allow flow of the charge pump through it based on differential pressure between them i.e., allows flow from the high pressure to low pressure side and not vice versa**.**

A 3 port 3 position valve is also used together with a relief valve with a **15bar** setting placed downstream of the directional valve. The relief valve is always connected to the low-pressure line.

Two other relief valves with a **450bar** pressure setting are used to limit the pressures on the high-pressure lines as said previously.

A constant external torque is applied to both motors (both of max displacement **75cc/rev**) through a constant ratio 1:1 gear coupling both motors, this also means that both motors will always rotate at the same speed.

Input signals representing the displacement variations of both pump and motors during the simulation are set exactly as shown on figure 10 above.

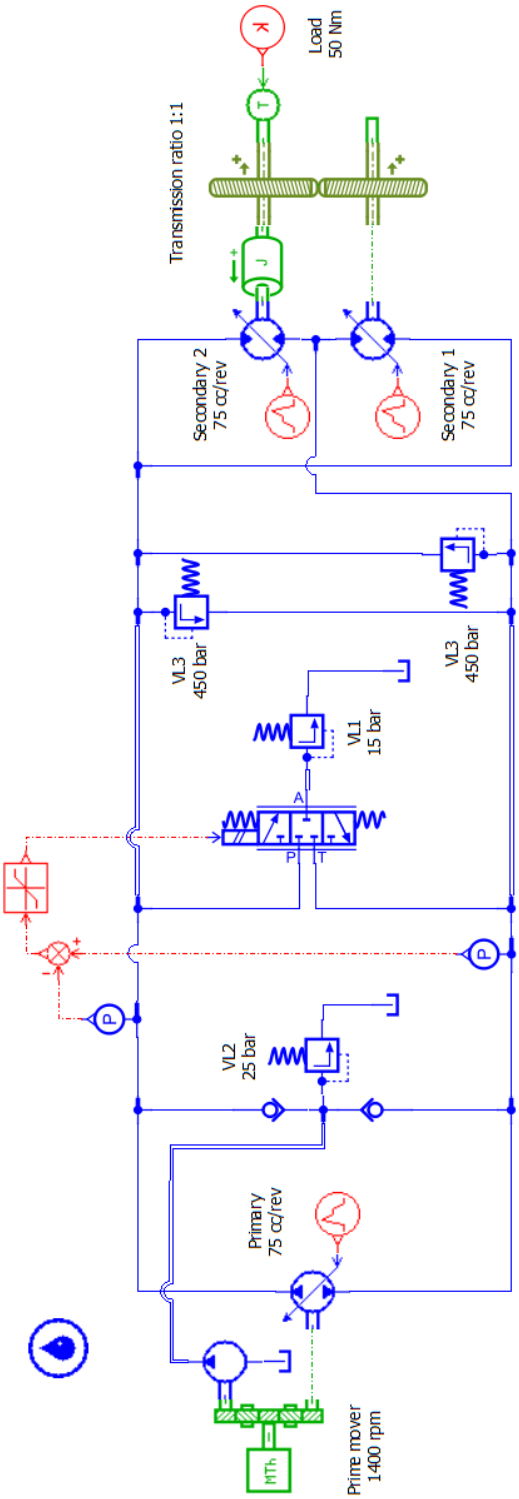


Figure 3-15 - Double motor hydrostatic transmission Amesim model

3.3 Amesim Model Description Of The Hydraulic Semi-Automatic Gearbox Control

The Amesim model starts with the modelling of the approximately fixed pressure flow generation unit (GAPFA) with the characteristics described in section 2.3.

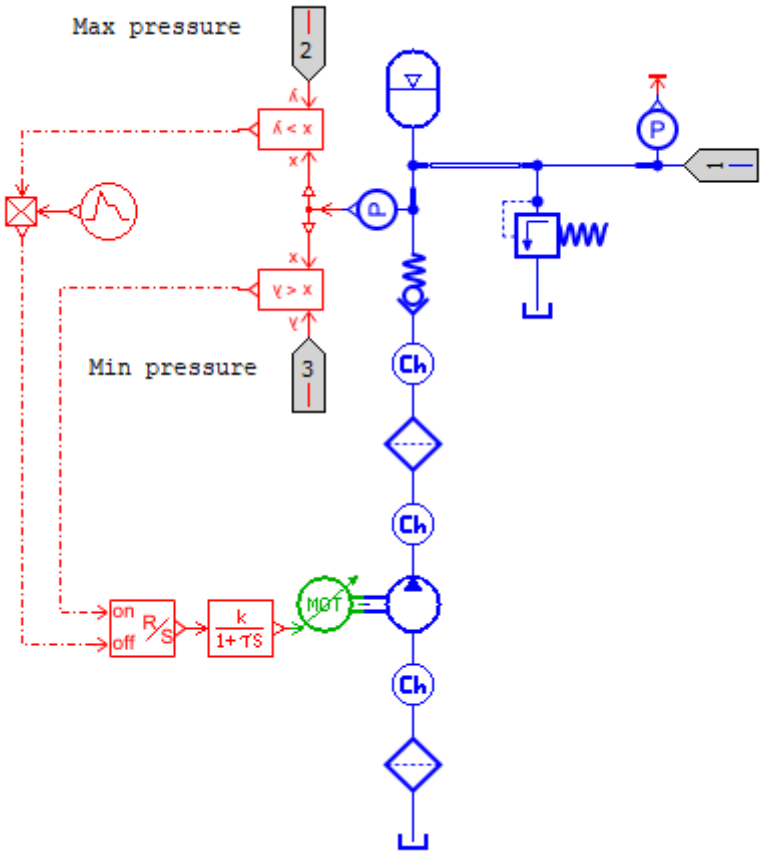


Figure 3-16 - Amesim model of GAPFA

As described in section 2.3, we can observe the circuit (in red) representing the mechanism for the motor activation and deactivation which is made essentially of the of a pressure sensor which generates the pressure signal that controls the motor.

The DF, directional flow control valve which serves actuator AF is a customized 3-position 3-port directional control valve. A displacement sensor connected to the actuator measures the actuator position x* which is controlled using a negative feedback mechanism by a P.I.D controller comparing it to an input signal x and eventually regulating the flow areas so that the actuator displacement follows the reference displacement signal as closely as possible.

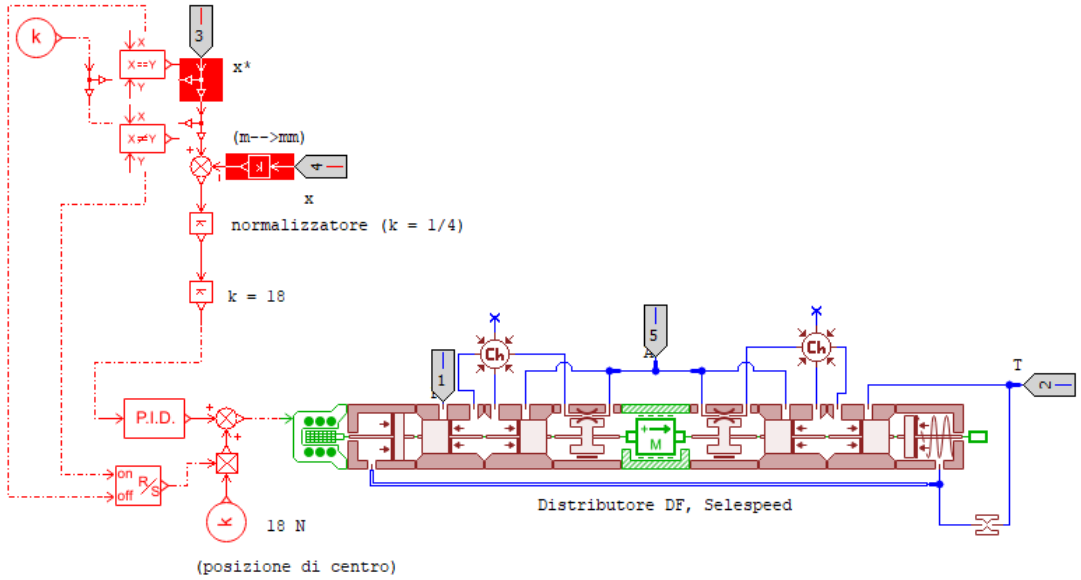


Figure 3-17 - Customized directional valve DF with negative feedback control

The DS directional control valve serves the actuator AS which enables the gear plane selection. It is a customized directional flow control valve which is actuated by an external on/off signal.

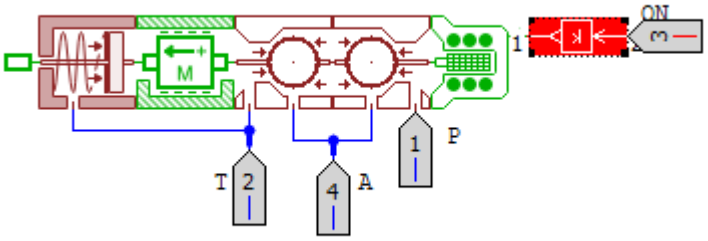


Figure 3-18 - Customized directional valve DS with on/off external actuation

The DI directional control valve serves actuator AI enabling the engagement and disengagement of gears. There are two valve which pressurizing each a chamber of the actuator. A displacement sensor connected to the actuator measures the displacement and interpolates the signal on using a table in order to obtain a force that represents the external load. This load signal together with the external on/off signal determines the actuation force operating the valve. It should be noted that the circuits and valves DI1 and DI2 are identical but just their actuation sequences vary.

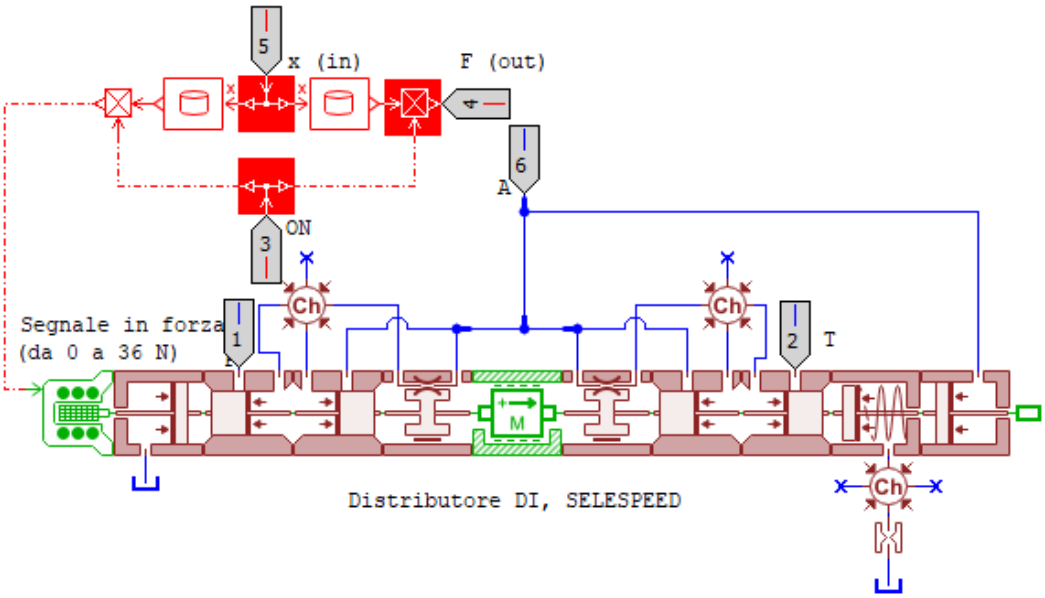


Figure 3-19 - Customized DI directional valve with actuation circuit

The overall circuit is as shown on the next figure where the customized valves are represented with simpler valves (in black).

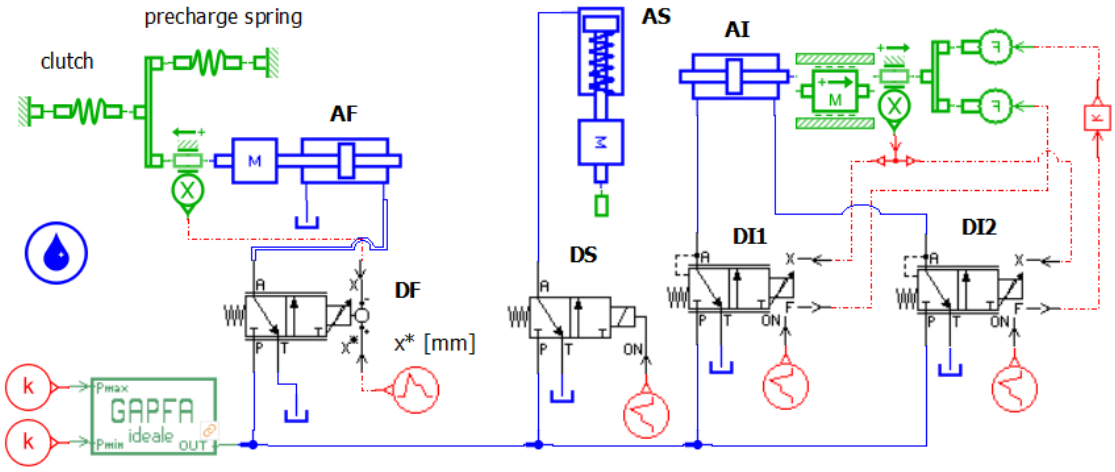


Figure 3-20 - Selespeed Amesin model

Since on Simscape it is not possible to design customized valves, a simplified version of the Selespeed Amesim model is done where the customized valves are replaced with simpler directional valves gotten from the Hydraulic library so that both the original model and the simplified model work similarly with little differences.

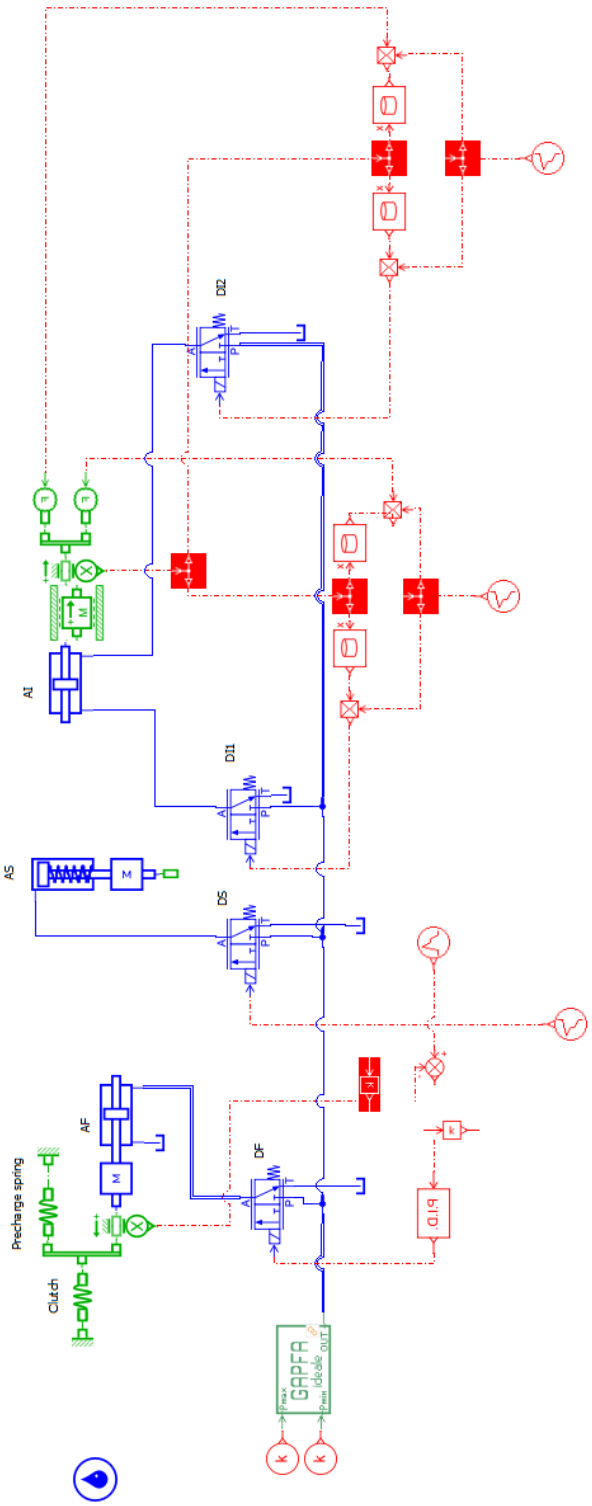


Figure 3-21 - Simplified Amesim Selespeed model

Chapter 4

SIMSCAPE MODEL CONSTRUCTIONS FOR SYSTEMS UNDER ANALYSIS

In this section the systems under study are reproduced on Simscape fluids and the various parameters are set for each component to have properties as close as possible as those components used in building the systems on Amesim. In some cases, the components are not identical and replaced by similar components which yield identical results of the systems. It should be noted that the aim is to create similar systems not necessarily using the same components also because the icons, operating principles, and parametrization of some these components on both platforms vary for some significantly.

4.1 Simscape Model Construction Of Power Steering Unit

The first step in creating the power steering unit model on Simscape fluids was creating a signal which represented the driver's input from the steering wheel and in this case the steering wheel velocity signal was used instead of the steering angle directly because of the presence of an ideal angular velocity source which yields as output an angular velocity starting from an input speed signal.

The speed signal is represented based on that obtained from the Amesim model. The figures below show the signal builder together with the ideal speed source on Simscape.

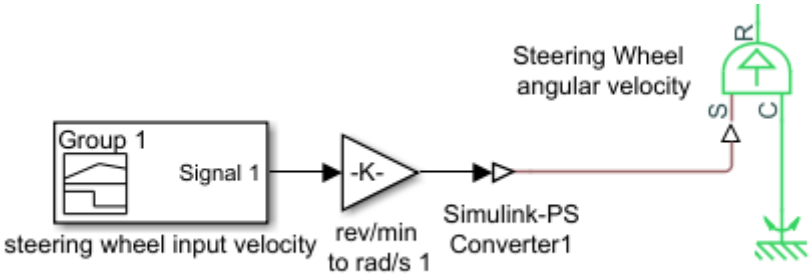


Figure 4-1 - Signal builder and ideal speed source blocks on Simscape fluids

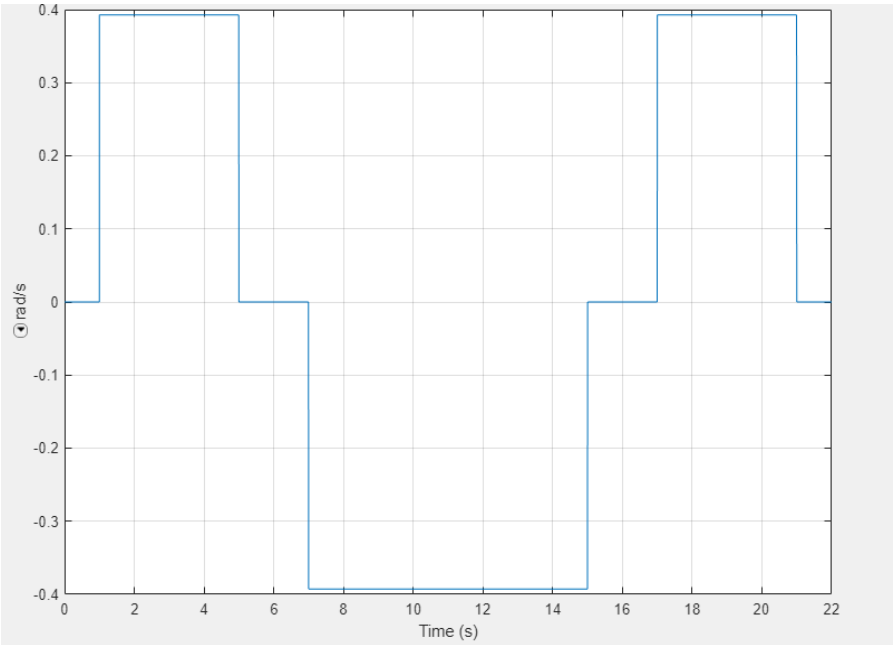


Figure 4-2 - steering wheel input signal

A Simulink gain block with a constant value to convert from **rev/min to rad/s (2π/60)** is used together with a Simulink to physical converter (It converts Simulink signals to physical signals). The output signal from the ideal speed source is transferred through a rotational spring which represents the stiffness of the steering column with the same parameter as that used on Amesim. A block is also used to represent the rotational inertia of the steering column as shown on the diagram below.

Figure 4-3 - rotational spring (C is the control port and R the reference port)

Figure 4-4- Inertia block on Simscape

The rotation on the steering wheel causes the rotation of the spool relative to the sleeve this rotation is represented by rotational spring identical to that used for the steering column with a smaller stiffness **K = 1.227Nm/degree,** the relative movement between spool and sleeve is measured using and rotational motion sensor and a block is used to represent the maximum relative rotation between the spool and the sleeve **+/- degrees** and also represent the hard stop characteristics when the spool and sleeve are in contact (i.e. stiffness **K = 11616.72Nm/rad**) and a block simulating the torsional damping is also included as shown below.

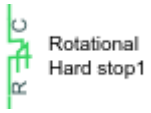


Figure 4-5 - maximum rotation and hard stop

Figure 4-6 - Rotational damper

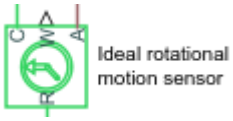


Figure 4-7 - ideal rotational motion sensor

The complete assembly of the spool and sleeve is shown below with the signal from the rotational sensor measuring the relative rotation that will be used to determine the passage areas to the double acting actuators.

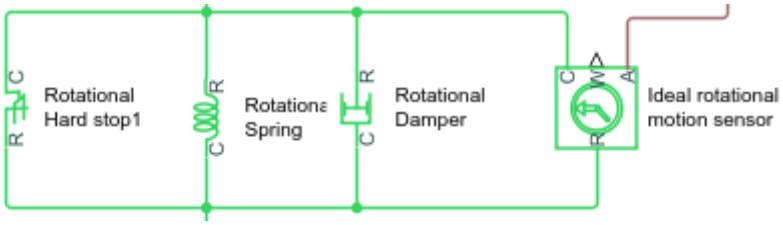


Figure 4-8 - spool sleeve assembly

The rack pinion connection is represented with the block shown below and the pinion stiffness is also taken into account with a rotational spring and inertia with the same parameters as those used on Amesim. i.e., **pinion radius r = 10.36mm** and pinion stiffness **K = 2277.9Nm/degree** and Inertia **J = 3.12245e-05 kgm^2**

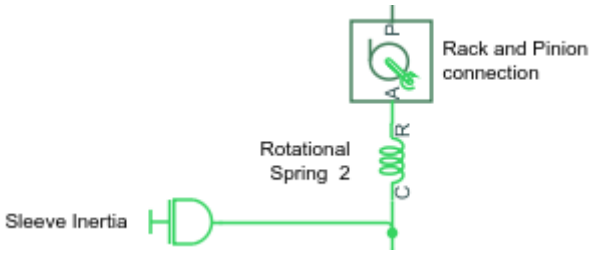


Figure 4-9 - rack and pinion connection

The translational assembly is made of a translational mass **m = 3.44kg** representing the rack which is rigidly connected to the double acting cylinder. A translational spring of stiffness **K = 200000 N/m** is fixed to a hard stop on one end and to rack on the other and is used together with a translational damper to impose an external load on the steering system.

Figure 4-10 - rack mass

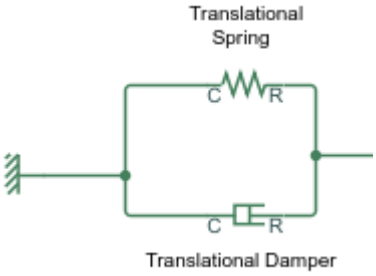


Figure 4-11 - Translational spring and damper imposing external load

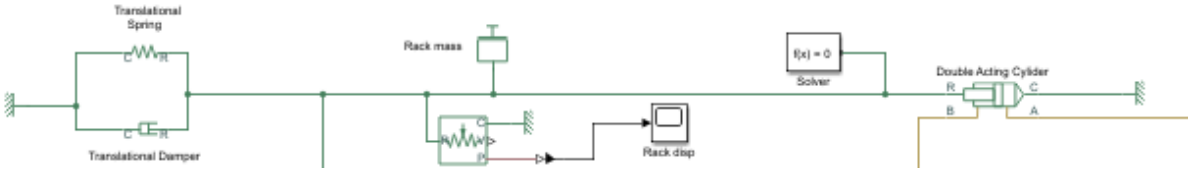


Figure 4-12 - translational assembly of the steering system

The hydraulic on Simscape starts from a signal builder which represents the pump speed profile and should be converted to a physical signal by a Simulink to physical converter and used together with an ideal speed source and connected to the fixed displacement pump with a displacement **V = 8.5 cc/rev**

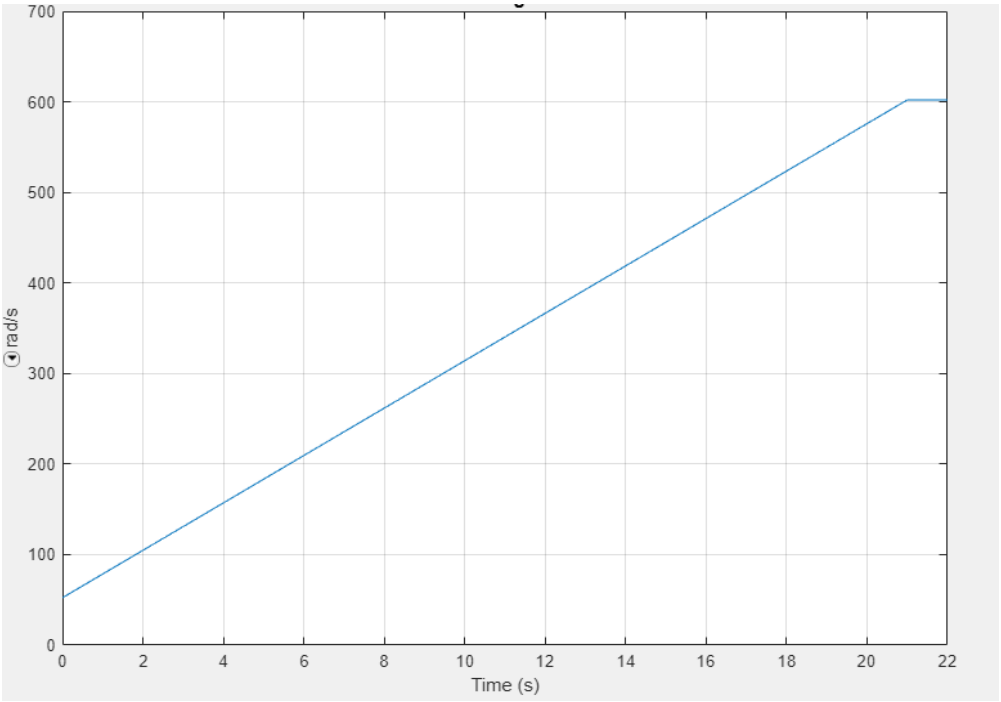


Figure 4-13 - pump speed profile

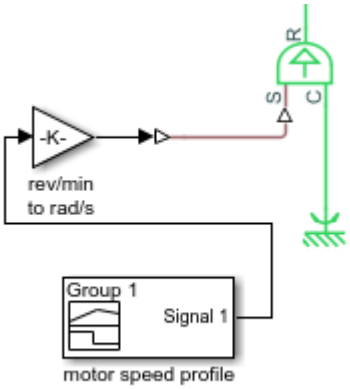


Figure 4-14 - signal builder and ideal speed sensor for pump speed profile

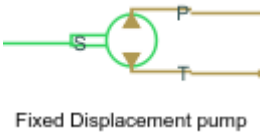


Figure 4-15 - fixed displacement pump (port P is the delivery port and port T the suction port)

The flow regulation in this case is done by a component different from the one used in Amesim because of the unavailability of an RQ3 flow control valve in the Simscape fluid library. Instead, a pressure compensated 3-way flow control valve is use and its parameters in order to have it settings as close as possible to that of the RQ3 flow control valve used on Amesim.

Figure 4-16 - pressure compensated 3-way flow control valve

This component normally considers an input signal that determines the variable orifice area by associating the control member stroke to an area. The area **A = 9.62e-6m²** in this case is gotten from the diameter **d = 3.5mm** of the metering restrictor SM on Amesim.

The pressure setting is gotten from the VLD valve setting i.e., the spring force **F = 38N** at 0 displacement, spool area **A = 2.27e-04m²** so we will have.

- Cracking pressure $p^* = \frac{F}{A}$ = 1.67 bar
- Pressure variation during valve regulation due to spring compression $\Delta p_{max} = \frac{k*x}{A}$ = 64190.65N/m² (0.64bar) where x =15mm is the maximum spring compression during regulation (obtained from the Amesim model VLD settings)
- $p_{max} = p^* + \Delta p_{max}$ = 2.31bar represents the valve maximum operating pressure

The above settings are those required for the valve on Simulink.

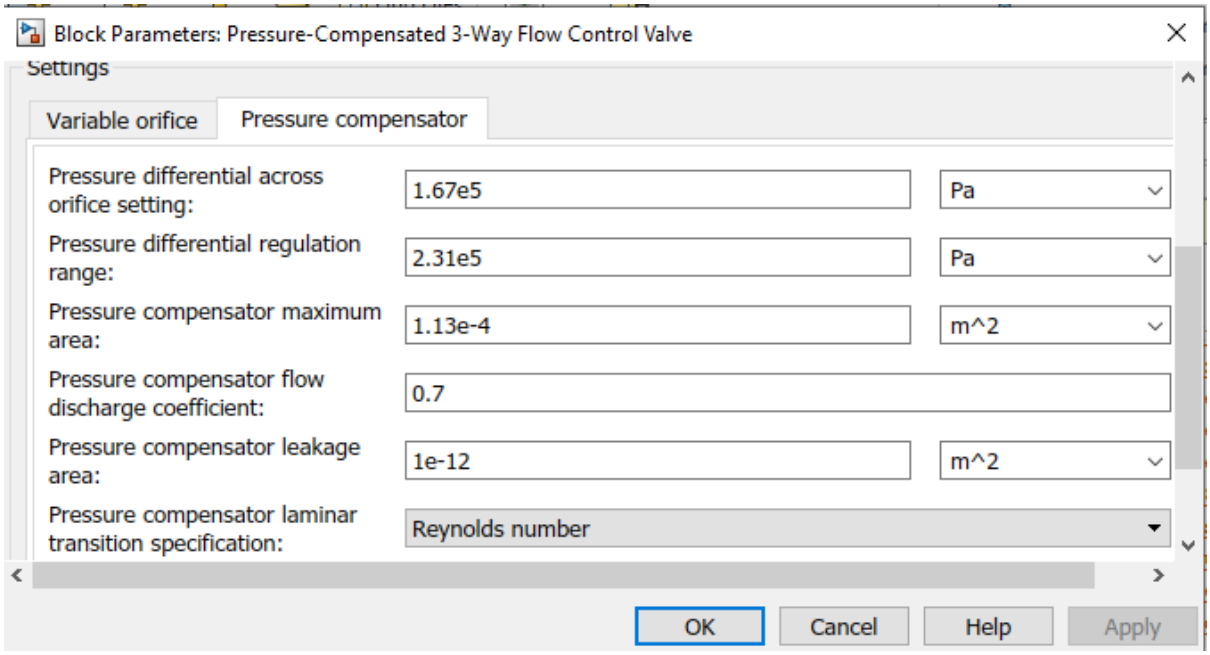


Figure 4-17 - Pressure-compensated 3-way flow control valve settings

The relief valve on Simscape is placed upstream the flow control valve ad the settings like that used on Amesim.

- Orifice diameter d = 3.35mm
- Maximum area A = 8.81e-6m^2
- Spring force at 0 displacement F_0 = 73N
- Spring stiffness = 27000N/m
- Cracking pressure p* = $\frac{F}{A}$ = 82.82bar
- Max pressure variation during regulation $\Delta p_{max} = \frac{k*x}{A}$ = 38.81bar with x = 1.267mm
- $p_{max} = p^* + \Delta p_{max}$ = 121.63bar

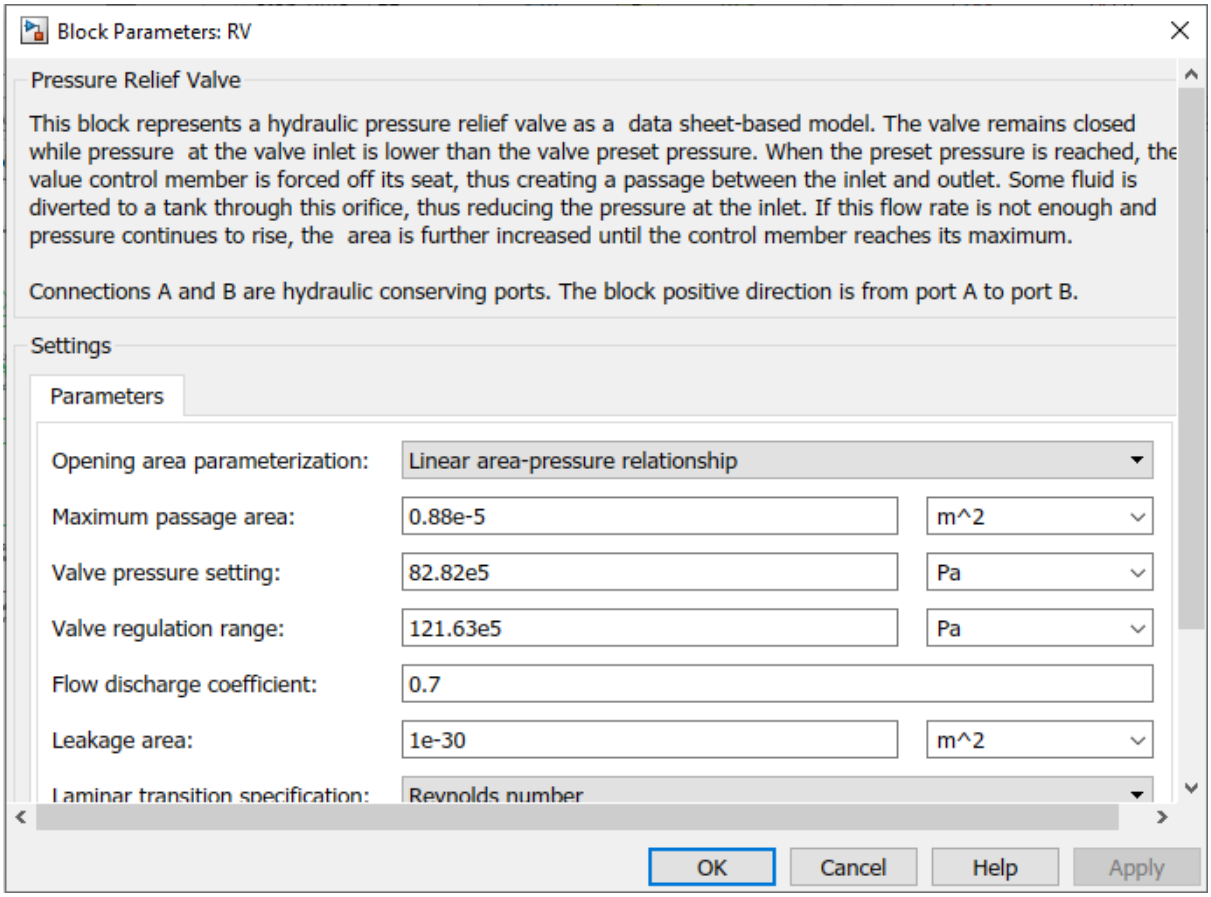


Figure 4-18 -Simscape relief valve parameters

The flow then reaches the 4-port 3-direction flow control valve which as said before is physically represented by the spool-sleeve passage areas and the passage area variations are due to the relative angle between the spool and sleeve during a steering manoeuvre. This mechanism is represented on Simscape as an assembly of 4 flow restriction valves connected to each other as shown on the figure below. The passage area variation of each flow restriction valve which corresponds to the area variation during spool sleeve relative rotation is represented by an external signal (in our case is the relative angle between spool and sleeve obtained from the angular rotational sensor) and yields a corresponding passage area obtained from interpolation using the text data imported from Amesim. It should be noted that the relative spool rotation obtained in rads is be converted in millimetres to be compatible with the block's parametrization and is done using a constant Gain block connected to the ideal rotational sensor with units set as mm/rad.

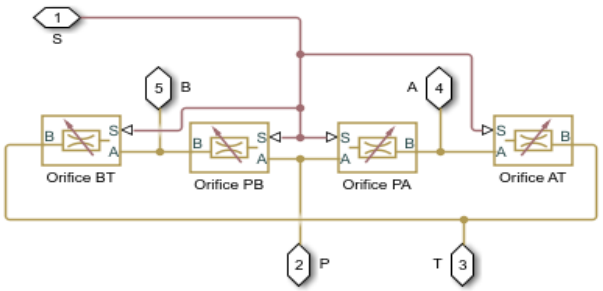


Figure 4-19 - 4 port 3 position directional flow control valve

The connection shown above represents the same connection used on Amesim and the parameters are set as shown below.

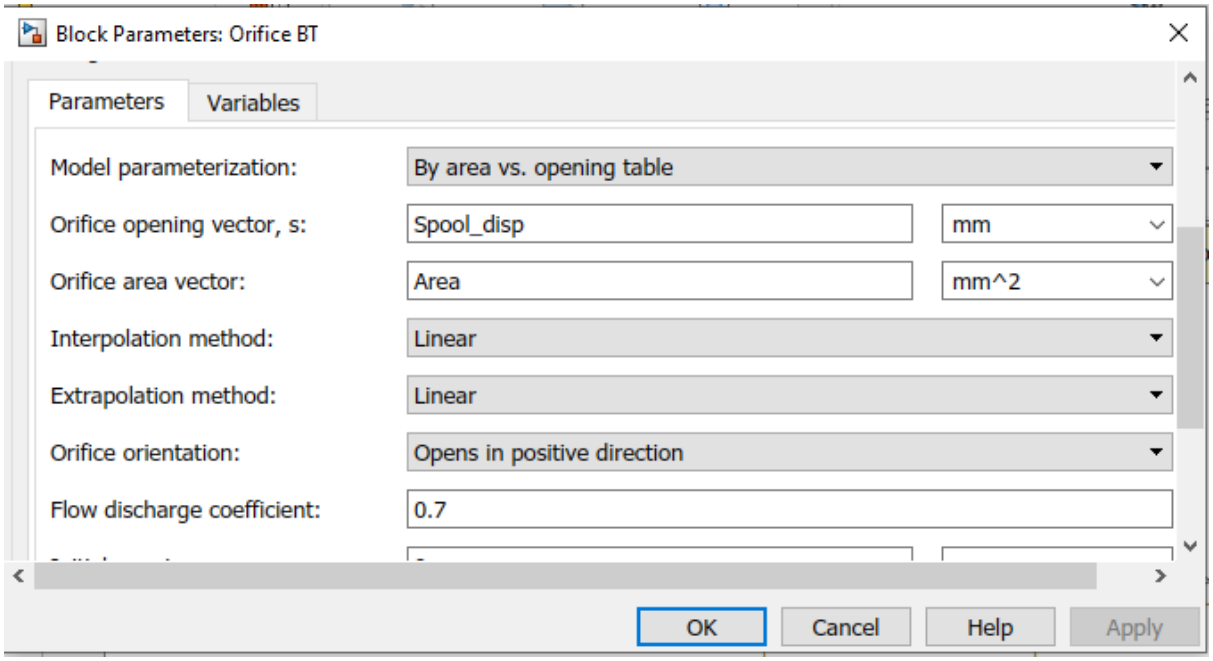


Figure 4-20 - Orifice area parameters

The interpolation in each orifice block is done using two vectors representing the spool displacement (spool_disp) and passage area (Area) obtained from a MATLAB code by importing a given the text file and creating these two vectors. A very important setting is the orifice orientation which coordinates the orifice opening or closing with respect to the input sign (e.g., **opens in the positive direction** means the valve opens for a positive input signal and closes for a negative input signal and vice-versa if **opens in a negative direction** is chosen).

In our case, Orifices BT, and PA open in the positive direction while Orifice PB and AT open in the negative direction.

The flow from the directional control valve then reaches the double acting cylinder where the pressure is unbalance on both sides of the piston causes a resultant force that moves the rack. The double acting cylinder is fixed at the port C and the rod is connected is connected to the rack through port A. The ports A and B and the input port to the left and right chambers of the cylinder.

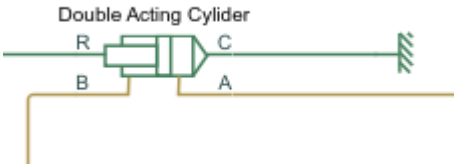


Figure 4-21 - Double acting cylinder

The parameters of the double acting cylinder are set like the one Amesim, but the icon on Simscape doesn't represent the parametrization i.e., the piston area can be set equal on both sides even if from the icon the area of the piston on port B should be different (smaller) from that of port A.

- Piston diameter d_{piston} = 38mm
- Rod diameter d_{rod} = 23mm

- Area A = π (d_{piston}^2 - d_{rod}^2)/4 = 7.19e-4m^2

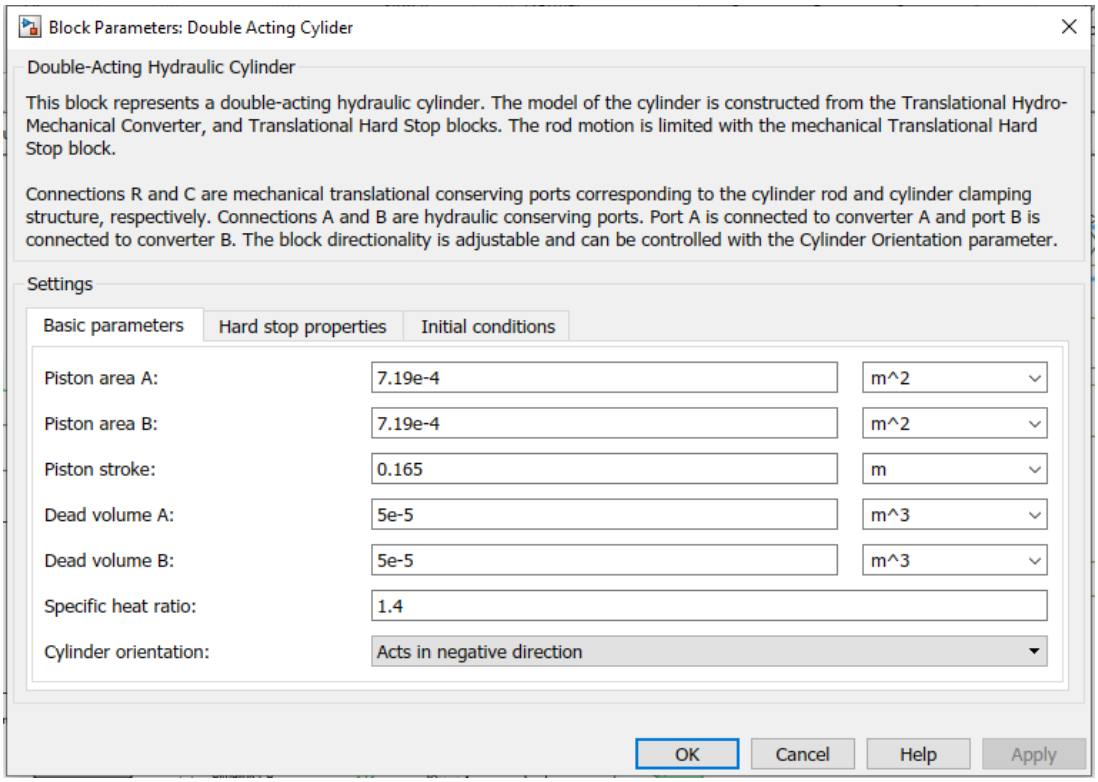


Figure 4-22 - Double acting cylinder settings

The stroke of the piston is equal to the rack stroke i.e., 0.165 and the displacement is half the stroke in both directions. The dead volumes are the chamber volumes when the piston is at the origin (its initial position).

Note that in this model, a left displacement is considered negative and a right displacement positive. The fluid properties of the hydraulic circuit are set connecting a hydraulic fluid block to any line of the hydraulic circuit. The fluid used for this model is the **ISO VG 32.**

Figure 4-23 - Hydraulic fluid

The overall circuit is shown on the next figure.

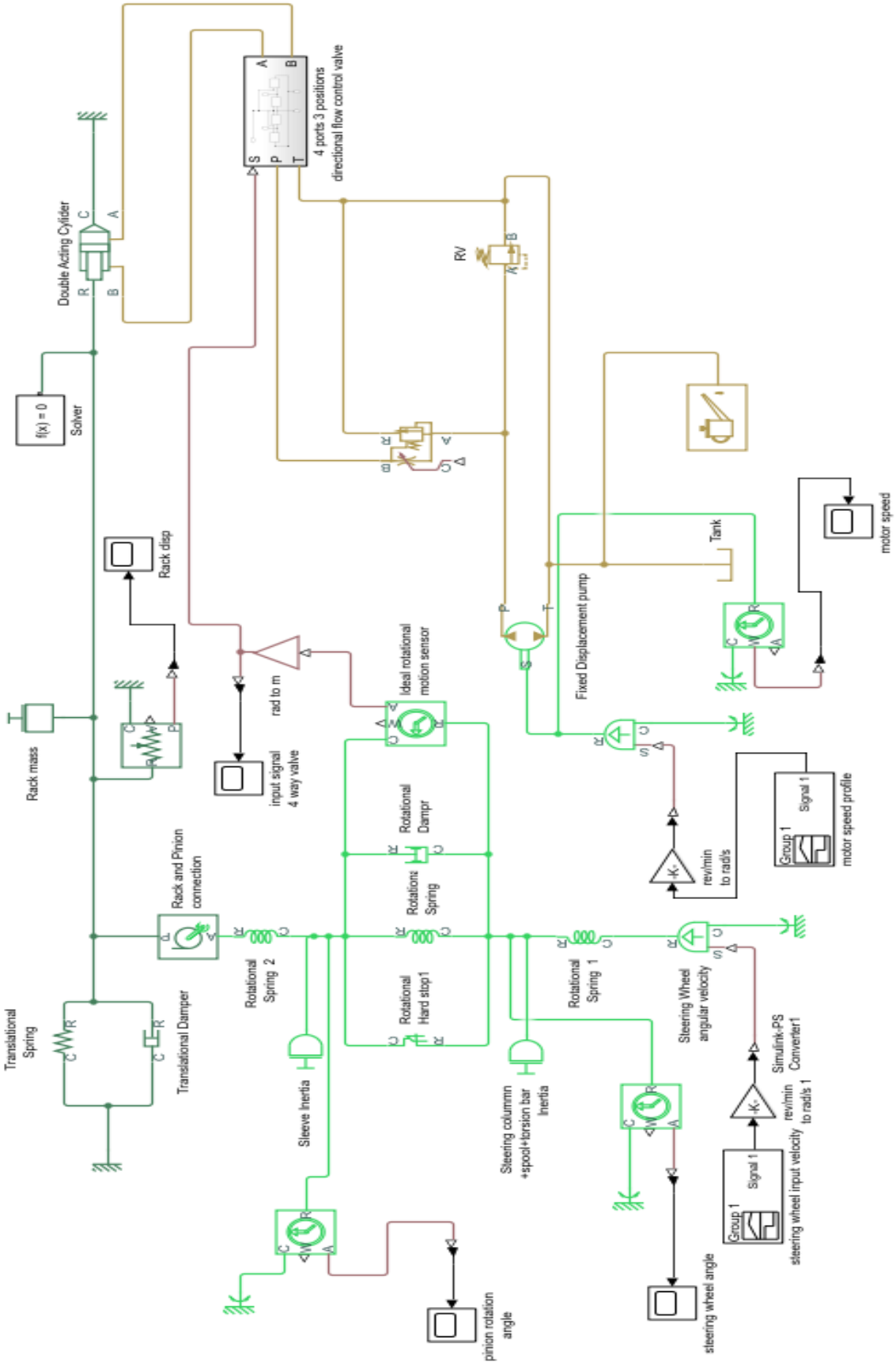


Figure 4-24 - Power steering circuit on Simscape fluids

4.2 Simscape Model Construction Of A Hydrostatic Transmission

The Simscape model for the hydrostatic transmission starts with defining the input signals which determines the variation of the displacements i.e., **the displacement modulation factor α** of the variable displacement pump and motors during the simulation. This is done as in the previous model with a Simulink signal builder.

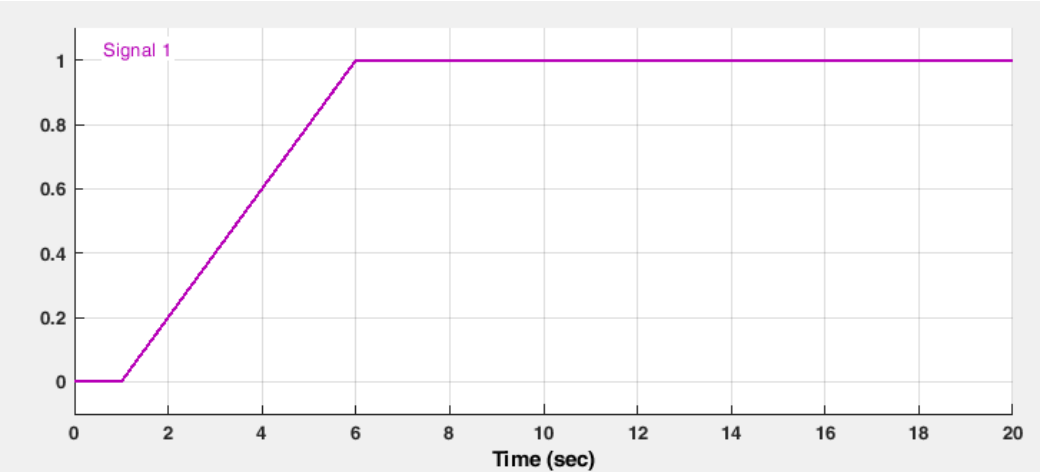


Figure 4-25 - Displacement modulation factor vs time for pump

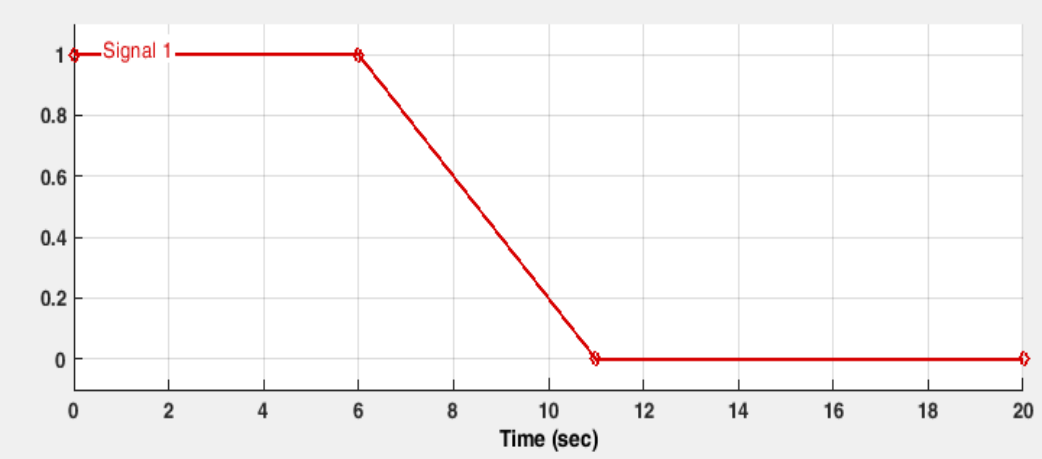


Figure 4-26 - Displacement modulation factor vs time for motor 1

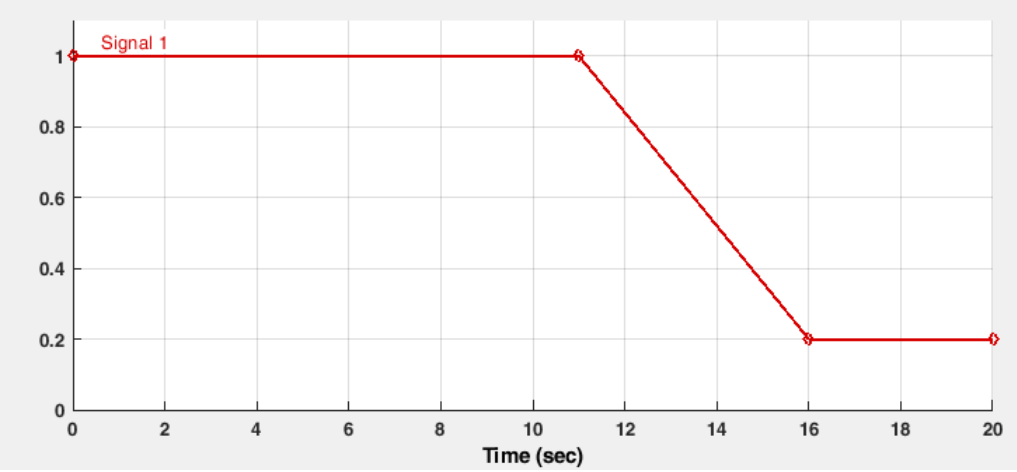


Figure 4-27 - Displacement modulation factor vs time motor 2

It can be seen from the previous figures that the displacement variation sequence of the pump and motors is identical to that earlier described in section 2.2.

These signals will be used together with an interpolation vector created during the component parametrization to determine the displacements of the pump and motors during the simulation.

A Simulink-physical converter and gain block is also used coupled to these signals to convert them to physical signals (stroke) that are needed for the interpolation.

Figure 4-28 - Simulink-PS converter and gain blocks

The blocks representing the variable displacement pump and motor are made of 4 ports, The port S which represents the rotating shaft of the pump or motor, ports P and T represent the delivery and suction ports respectively for the pump and ports A and B are the input and output ports of the motor. The fourth port C is the input port for the displacement control signal.

The maximum displacements of the variable displacement pump and motors are equal i.e.

$V_{maxP} = V_{maxM1} = V_{maxM2} = 75cc/rev.$

It should be noted that the variable displacement pump and motor are invertible i.e., the direction of flow through the hydraulic ports are interchangeable and the shaft can rotate in both directions.

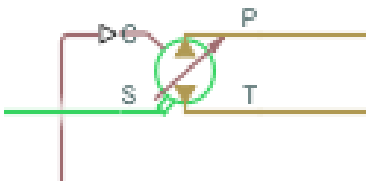


Figure 4-29 - Variable displacement pump

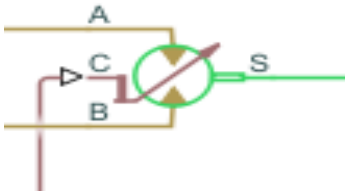


Figure 4-30 - Variable displacement motor

The charge pump used to compensate the leakages in the circuit is a fixed displacement pump with a displacement **V = 15 cc/rev.**

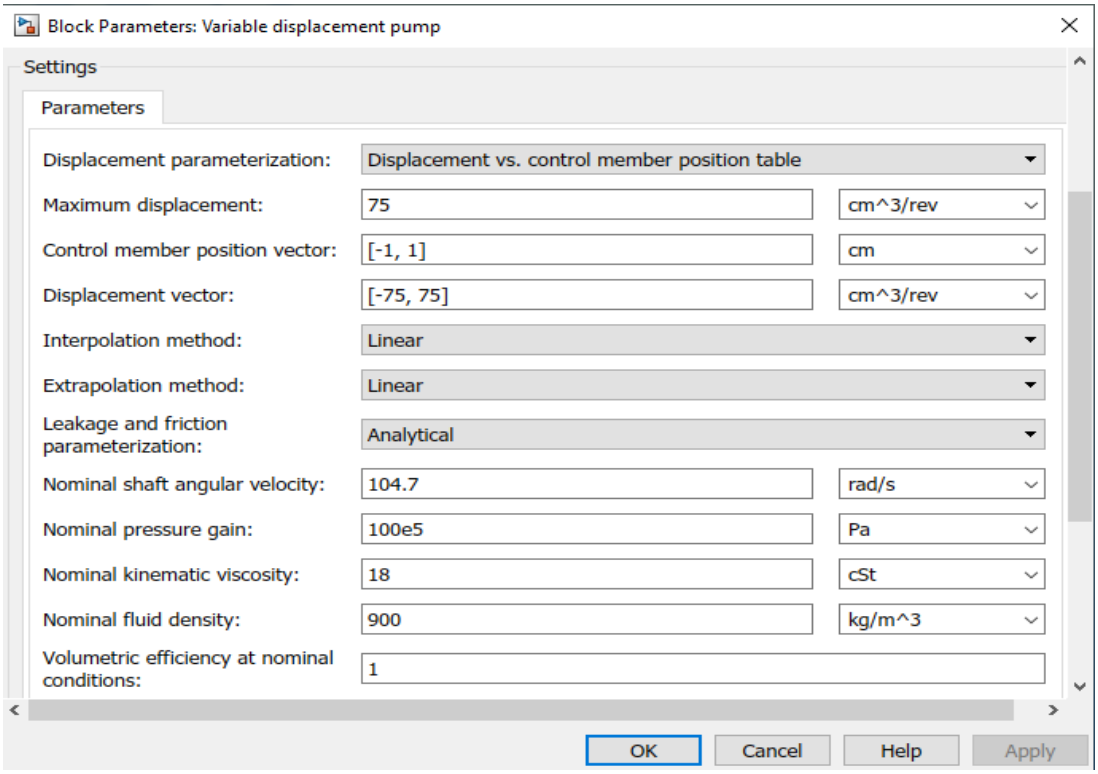


Figure 4-31 - Variable displacement pump settings

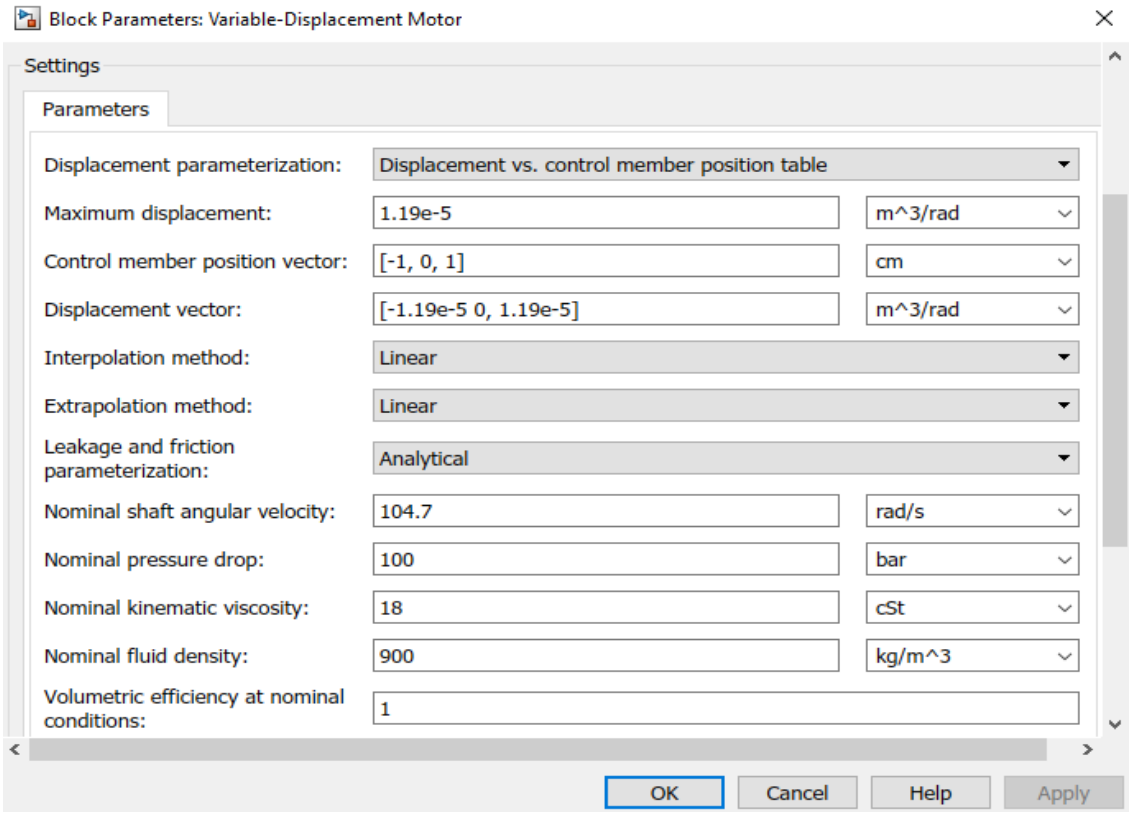


Figure 4-32 - Variable displacement motor settings

An ideal speed source determines the rotational speed and hence the flow rates of both the charge pumps and the variable displacement pump. The speed source rotates at a constant speed of **1400rev/min**.

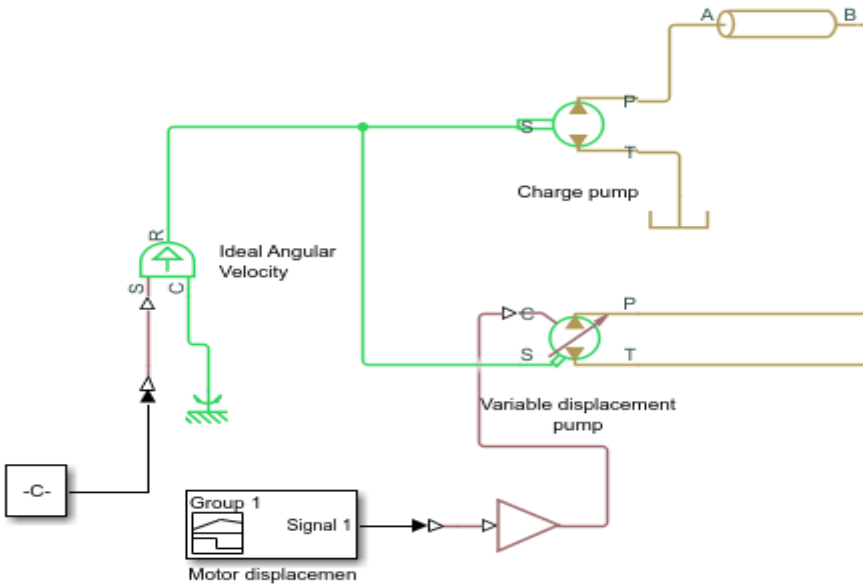


Figure 4-33 - Flow generation unit of the circuit (primary unit)

The load on the circuit is imposed by a constant torque source which acts on both motors during the entire simulation. The torque from the source in this case is **50Nm** and it will be seen from the results of the simulation that the torque on Motor1 reduces to zero since its displacement goes to zero.

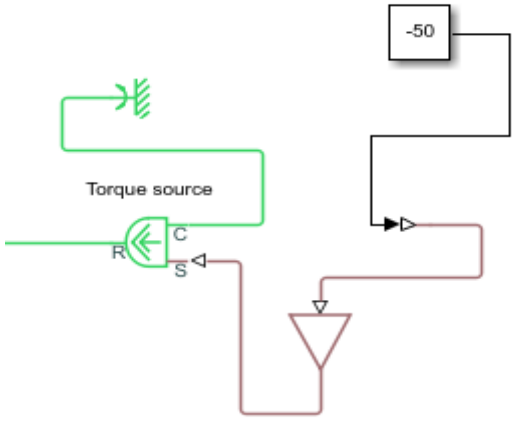


Figure 4-34 - Ideal Torque Source

Port S is a physical signal port, through which control signal that drives the source is applied. Positive signal at port S generates torque acting from C to R.

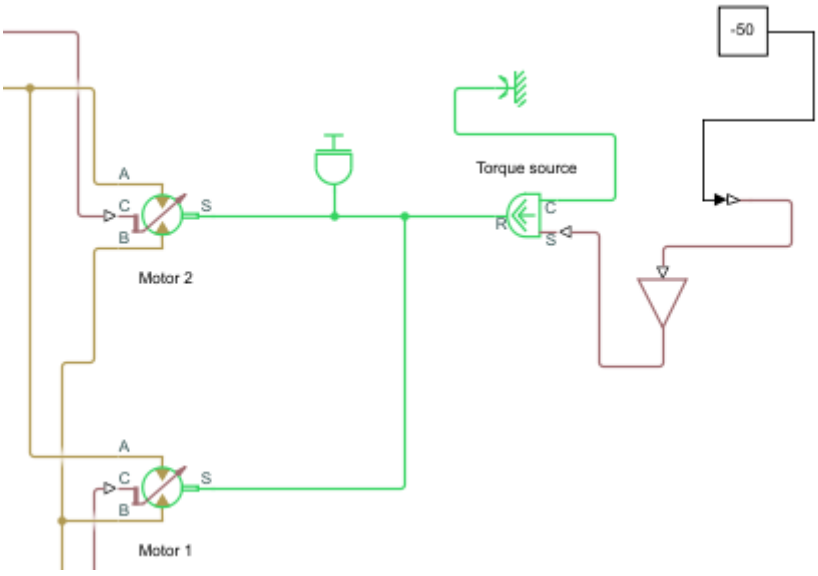


Figure 4-35 - Secondary unit of circuit

The relief valve RV1 is used as a safety relief valve on the low-pressure line and is set to **25bar** and a maximum pressure variation of **1bar** during regulation.

There are two check valves connected between the high-pressure and low-pressure lines of the circuit which allow the flow in one direction i.e., they are placed such that one valve allows the flow from the charge pump to the low-pressure because the pressure difference between its ports A and B is less than the cracking pressure (very small value) while the other valve inhibits the flow through it because the pressure difference between the ports A and B is lower than the cracking pressure. Two check valves are used because the circuit is reversible so if the pressure lines are inverted the circuit still works correctly.

Figure 4-36 - Check valve

It should be noted that the check valve used in this case has a spring setting since the check valve without spring is not available on Simscape. But the spring settings i.e., cracking pressure is set to very low value of **0.1Pa.**

The relief valve RV2 imposes the pressure on the low-pressure line to a constant value which corresponds to its cracking pressure of **15bar.** For this reason, the RV2 must always be connected to the low-pressure line, and this is done with a 3-port 3- position directional control valve actuated by an external signal.

This external signal that is used for the directional valve actuation is the output signal of a saturation block. This block imposes upper and lower bounds on the output signal. When the input signal is within the range specified by the Lower limit and Upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound.

The input signal of the saturation block is the difference between the signals from the pressure sensors placed on the high-pressure and low-pressure lines.

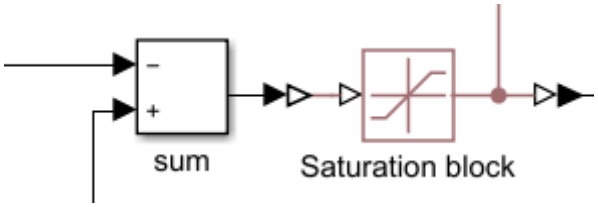


Figure 4-37 - Input and output of saturation block

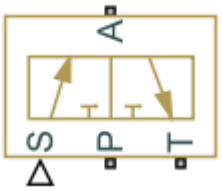


Figure 4-38 - 3-way directional control valve

Two pressure relief valves RV3 and RV4 with a **450bar** cracking pressure setting are put in the circuit to limit the pressure in the high-pressure line to a maximum value corresponding to its cracking pressure setting. The maximum pressure variation during regulation for both relief valves is set to **10bar**.

Two relief valves are used because of the reversibility of the circuit. This allows the high-pressure line to always be connected to a relief valve even when the load on the circuit is inverted.

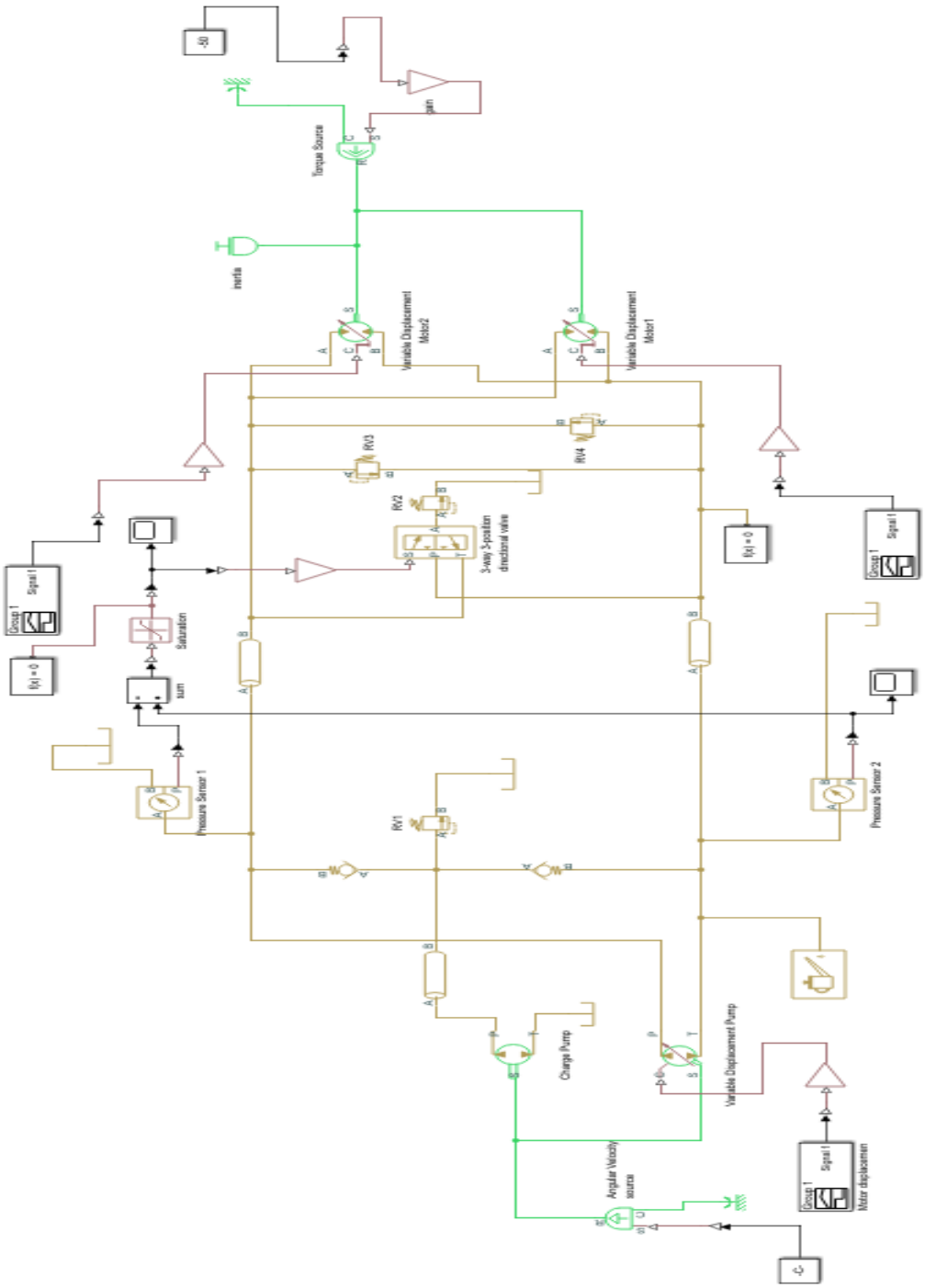


Figure 4-39 - Double Motor Hydrostatic Transmission Simscape Model

The characteristics of the fluid and the settings of the hydraulic pipes used in this circuit are shown below.

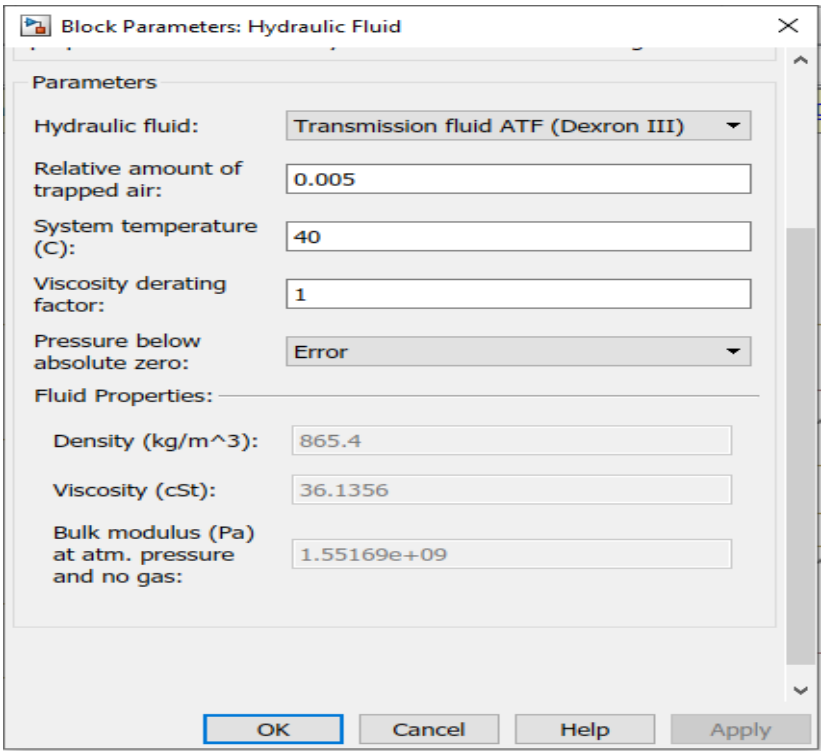


Figure 4-40 - Hydraulic fluid characteristics

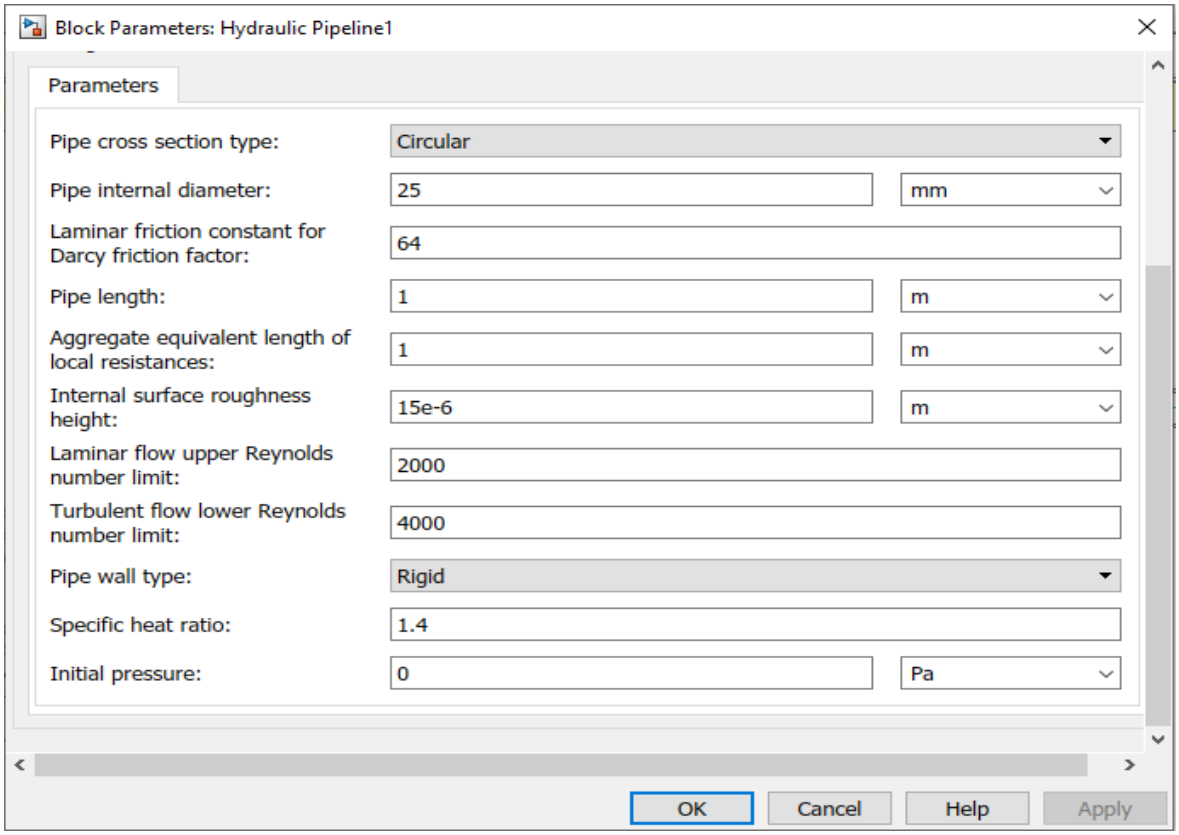


Figure 4-41 - Hydraulic pipeline settings

4.3 Simscape Model Construction Of The Flow Generation Unit of A Hydraulic Semi-Automatic Gearbox Control

The Simscape model construction of the hydraulic semi-automatic gearbox control (Selespeed) is done only on part of the system which is flow generation unit. To test for the functioning of this unit a simpler circuit is modelled where the user group is made of a fixed area flow restrictor which demands a constant flow rate from the flow generation unit. However, the flow generation unit works using a pump which is electrically actuated by a pressure switch.

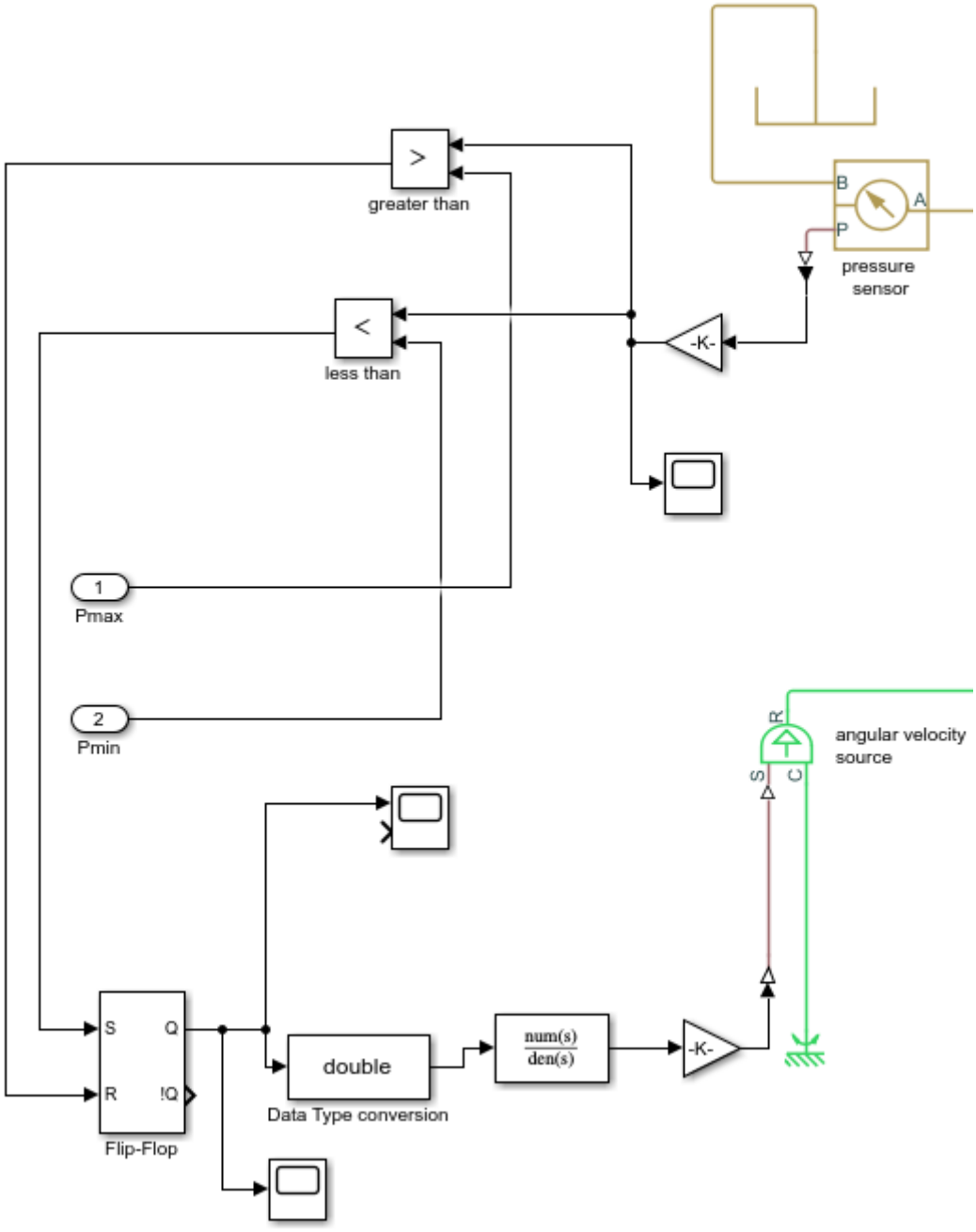


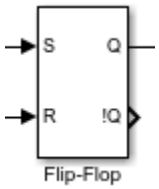
Figure 4-42 - Simscape pressure switch

As it is the case with the Amesim model a pressure sensor measures the pressure in the circuit downstream the check valve and compares it to the limit values imposed externally. If the pressure drops below the lower limit **37bar** the switch turns on the motor (on Simscape the motor is substituted with and angular velocity source). The pump sends fluid to the user group and the excess flow is sent to the accumulator and this continues until the pressure in the circuit reaches the maximum limit value of **55bar.** The pressure switch goes off turning of the pump. The flow to the user when the pump is off is supplied by the previously charged accumulator causing the pressure on the circuit to drop until it reaches the minimum value and the pump is re-activated restarting the cycle.

The on/off actuation of the angular velocity source is done with a set/reset flip-flop which works with the logic represented on the figure below.

S(set)	R(reset)	Qn(output)	!Qn(output)
0	0	Qn-1	! Qn-1
0	1	0	1
1	0	1	0
1	1	0	0

S and R are input port (note that the block interprets and a non-zero input signal as true and a zero input signal as false). The output from the flip-flop goes to a transfer function block whose output is the pump angular velocity.



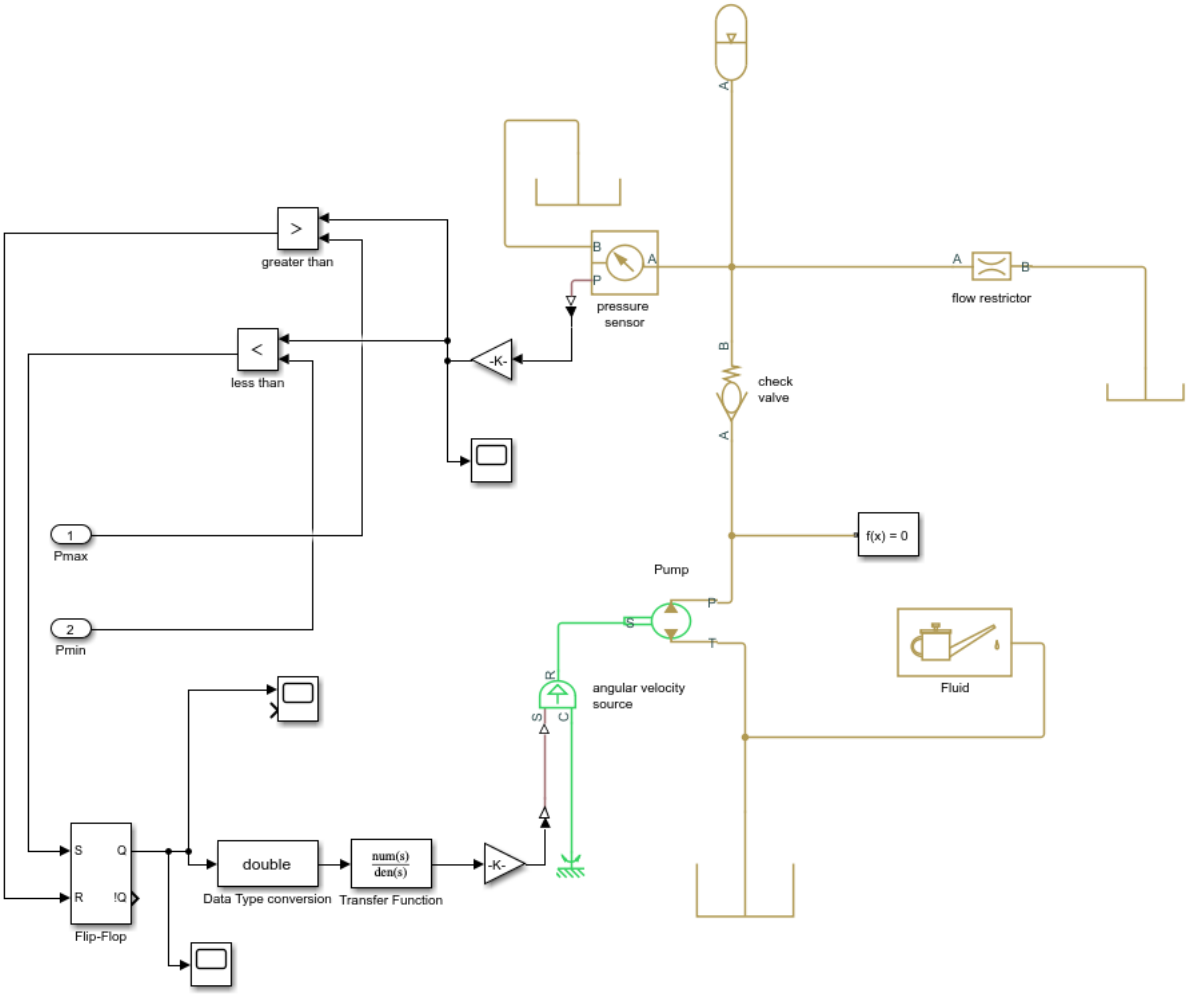


Figure 4-43 - Flow generation unit with constant flow rate user group

Chapter 5

RESULTS AND COMPARISONS

In this section, the various plots for each system are critically compared and commented to better highlight the differences between both simulation platforms. This is done overlapping the graphs obtained on both simulation platforms on a Simulink scope to better note the differences.

5.1 Amesim Vs Simscape Plots For Power Steering Systems

The characteristic plots of the power steering system will be exposed in this section for both Simscape and Amesim.

5.1.1 Steer Angle

The first curves to be compared is the steering wheel input angle signal. It should be noted that this is not an output of the simulation but rather an input or starting point for both platforms.

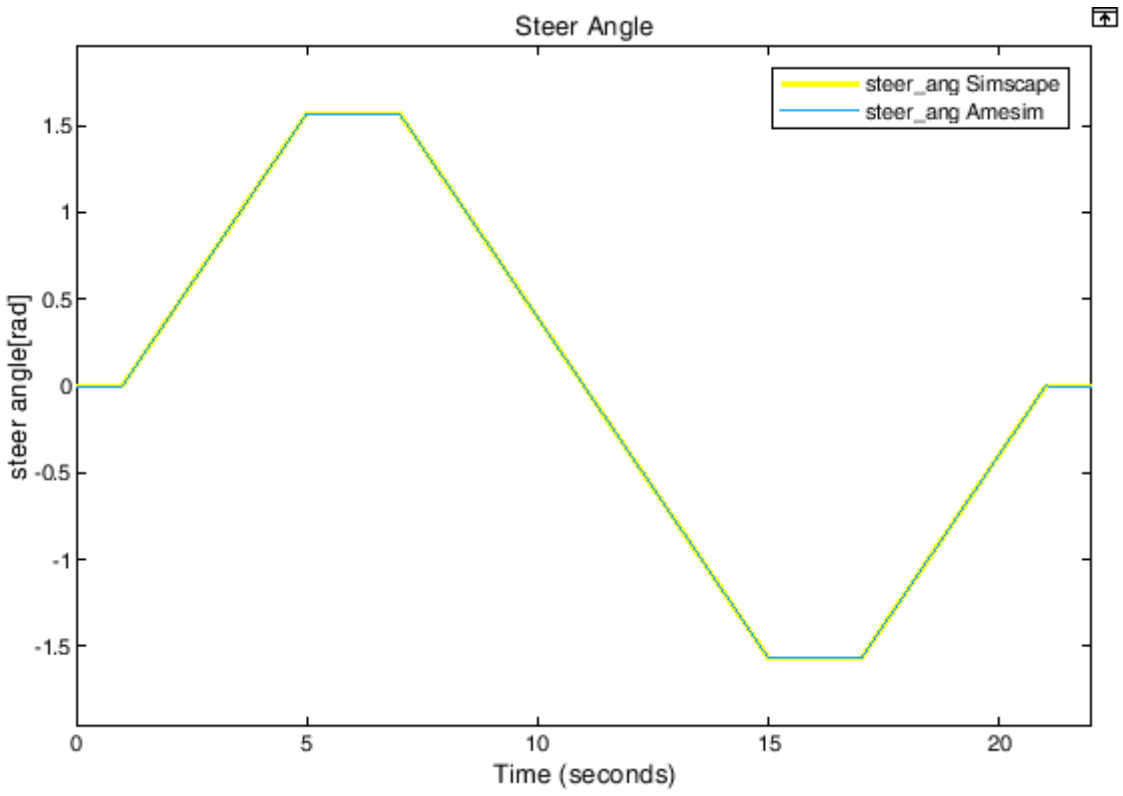


Figure 5-1 - steering wheel input angle in rads

Both plots are overlapped, and this indicates that the steering wheel input signals are identical for both simulations.

5.1.2 Pump And Flow Regulator Flow Rates

Another important input signal to be analysed is the pump speed profile which should also be identical for both simulations. Since the signal is imported into Simscape from Amesim using a MATLAB code and signal builder we are sure the pump speed profile is the same for both simulations. The flow rate profile is obtained from the pump displacement and is similar to the speed profile.

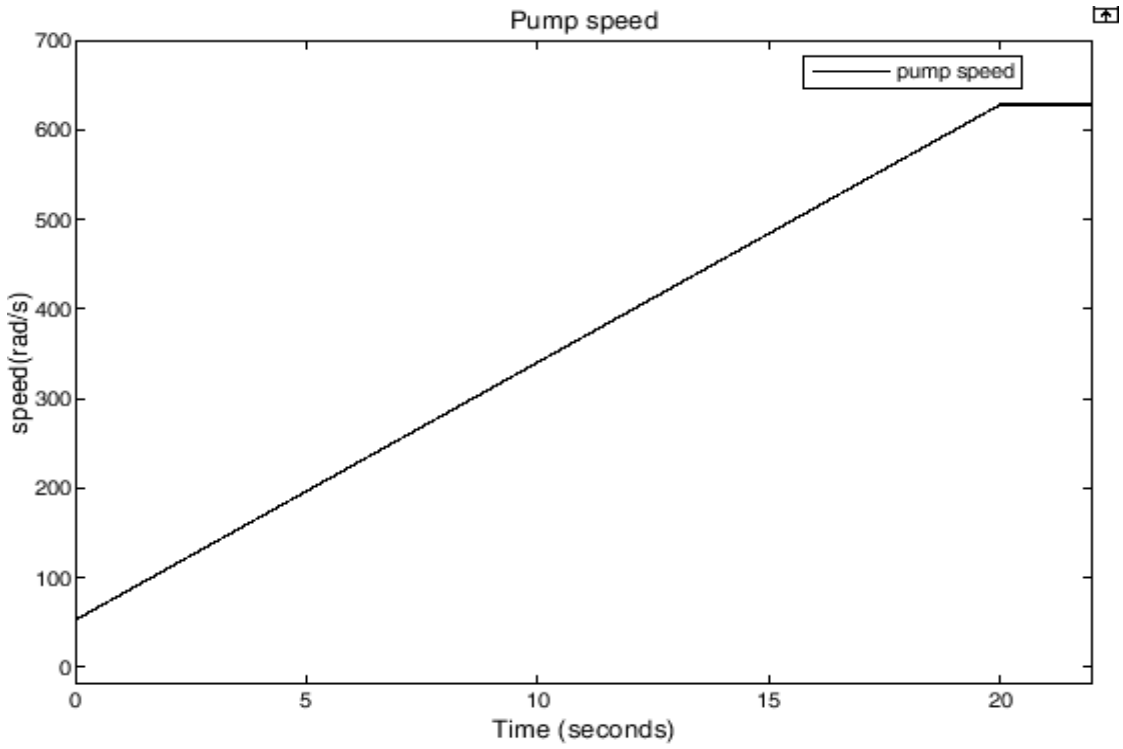


Figure 5-2 - pump speed for both simulations

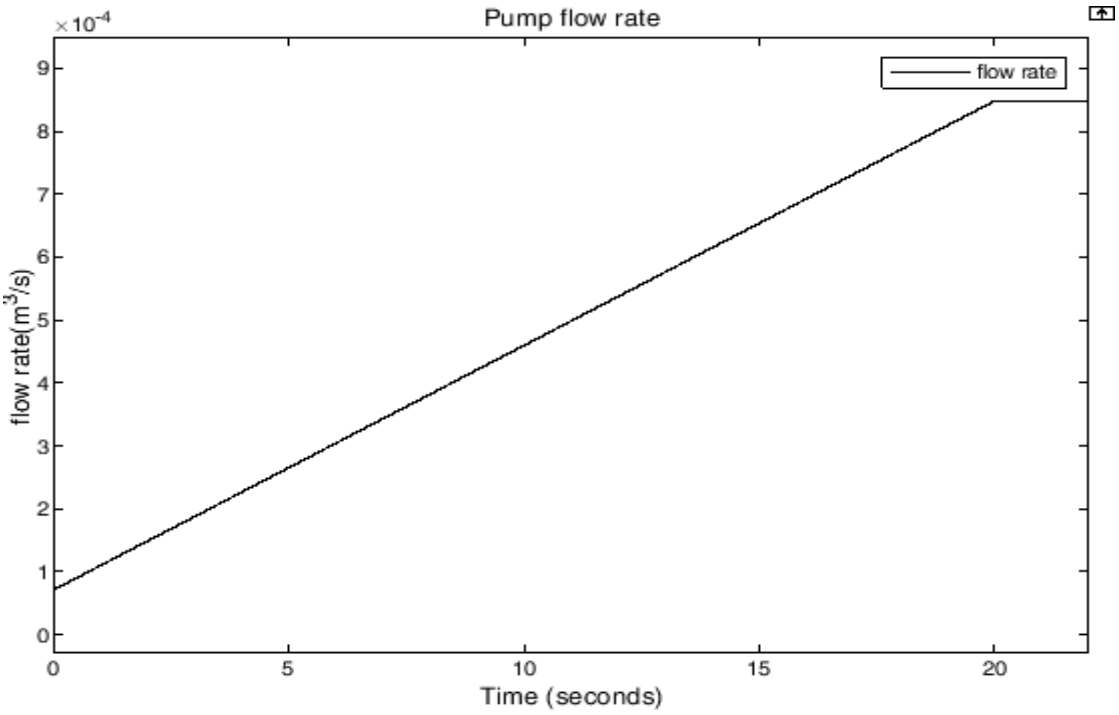


Figure 5-3 - Pump flow rate

The flow regulation valves as said before limits the flow to the actuator by discharging part of it back to the tank to avoid oversensitivity of the steering system at high engine speeds.

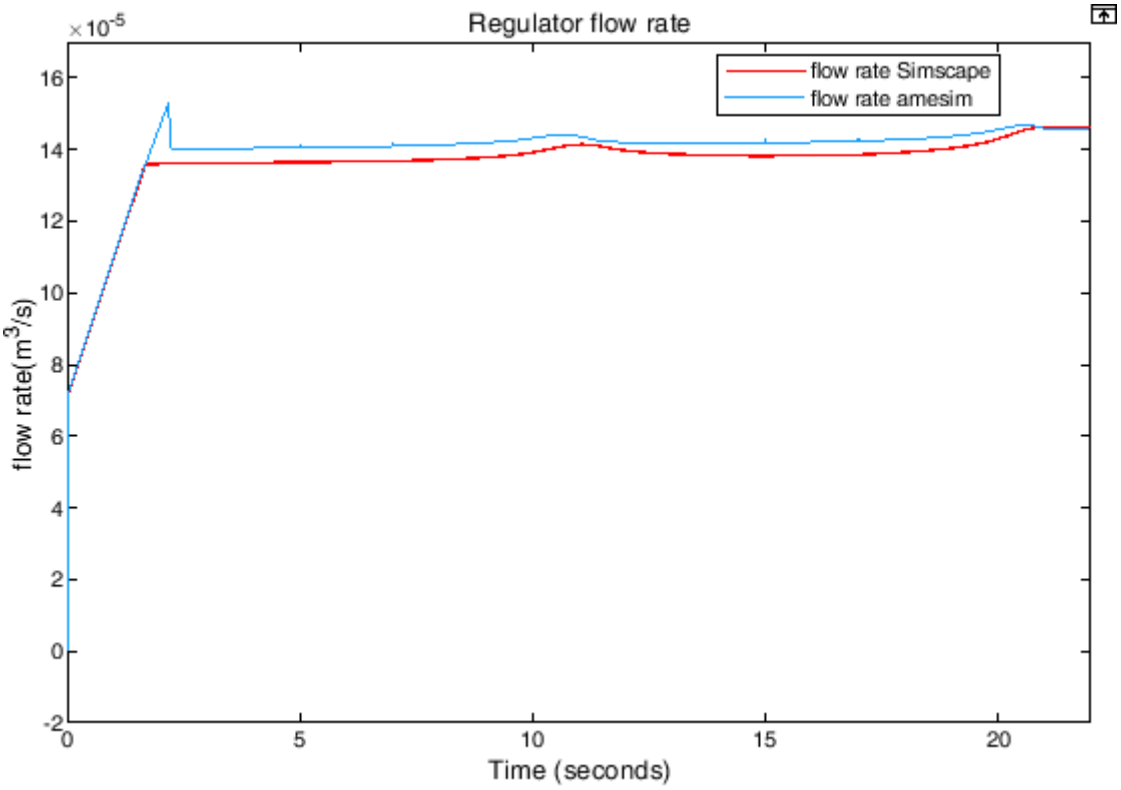


Figure 5-4 - regulation valve flow rate

It is seen from the figure above that the flow rate is slightly higher for the Amesim model because on Simscape the flow regulation valve used was not identical to that used on Amesim hence the

difference in flow rate. This is mainly due to the slight difference in the passage areas of the restriction valves (calculation inaccuracies).

5.1.3 Spool-Sleeve Relative Angle And Actuator Displacement

Another very important comparison is the relative rotation between the spool and the sleeve. This is very important because is what determines the passage area of the fluid to the actuator. On both platforms it is represented as a signal that is used as input to determine the passage areas of the ports of the directional control valves.

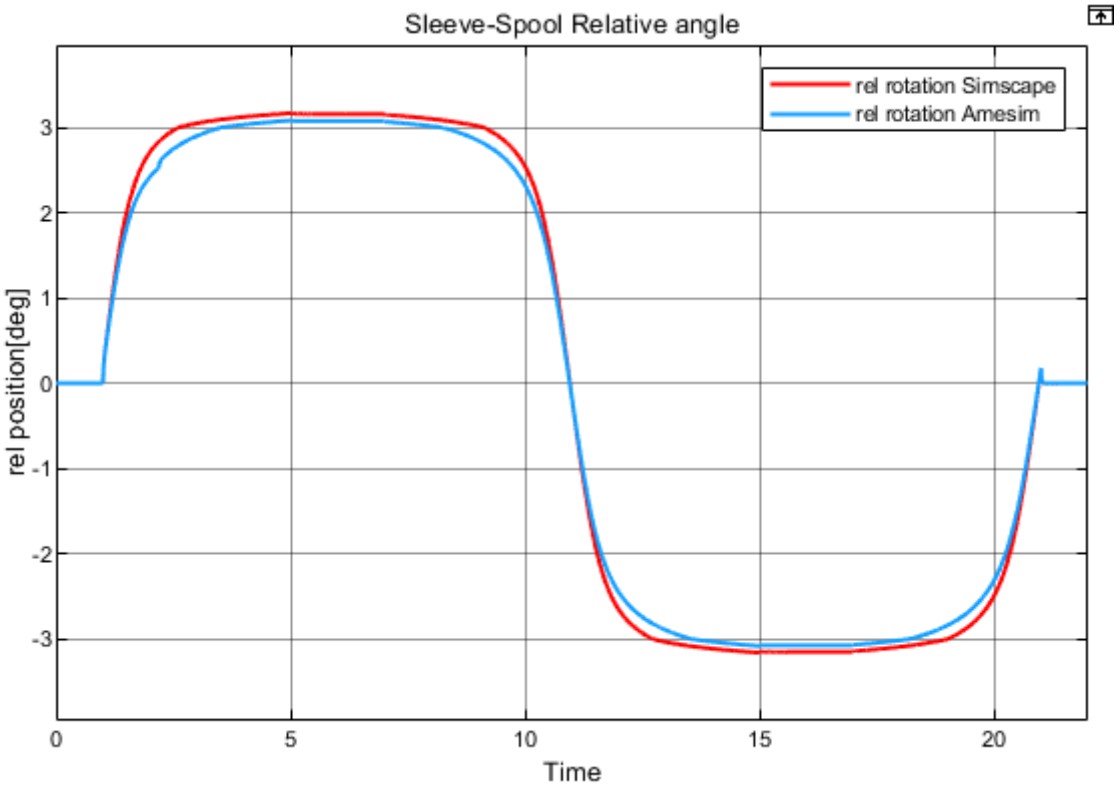


Figure 5-5 - spool-sleeve relative angle

From the relative angle plots it can be noted that they do not perfectly coincide with each other with the curve on Simscape having a peak slightly higher than that on Amesim which is due to the difference in parametrization of the blocks on both platforms.

Now the actuator displacement curves are compared for both simulations as show on the diagram below.

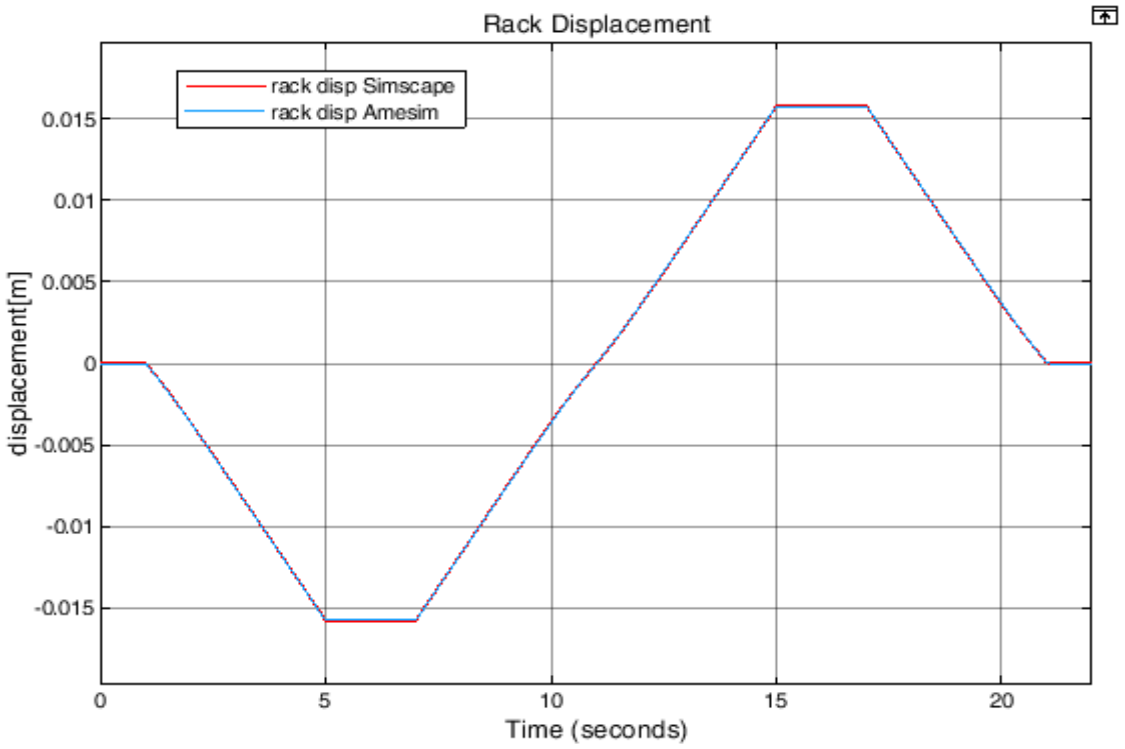


Figure 5-6 - Actuator displacement

The displacement is identical for both simulations as seen above (overlapping signals).

5.1.4 Double Acting Cylinder Pressures

The pressure on both sides of the cylinder is now evaluated on both models and are shown on the diagrams below.

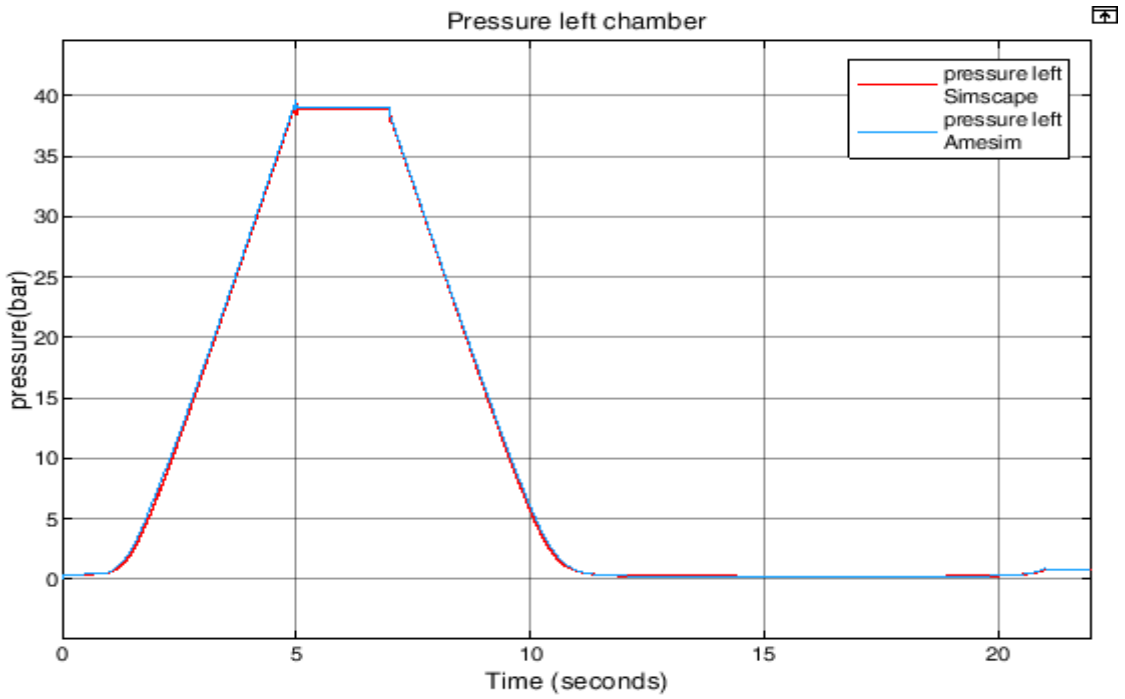


Figure 5-7 - left chamber fluid pressure

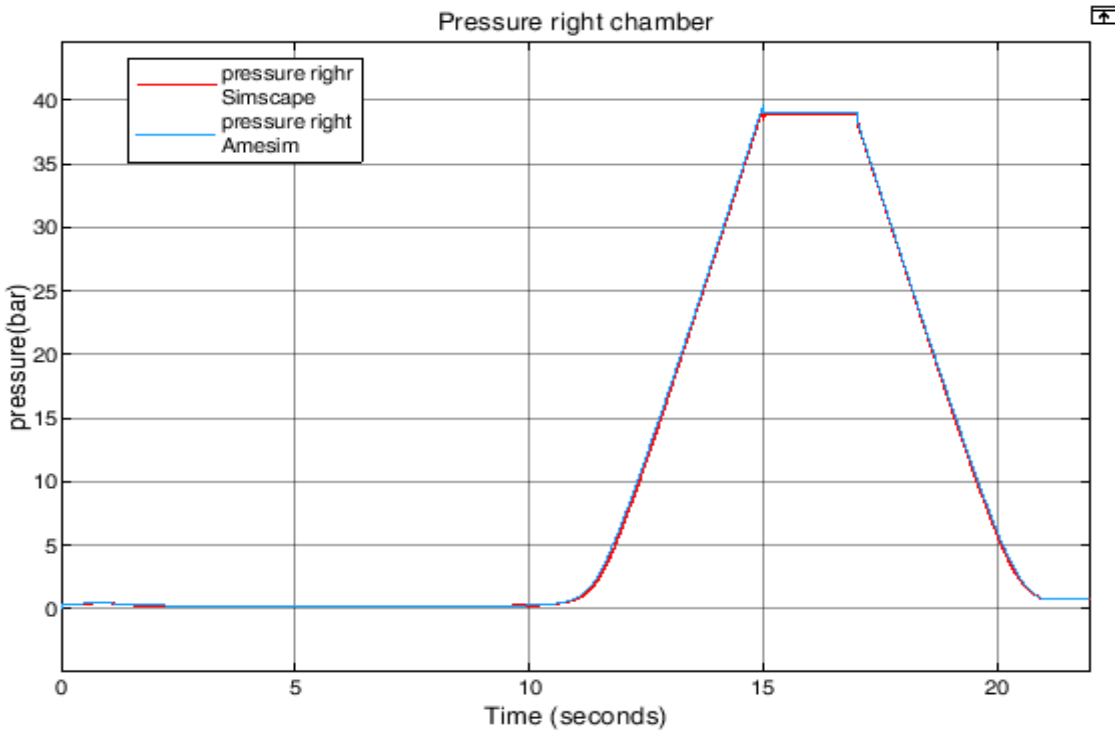


Figure 5-8 - right chamber pressure

It can be seen from the curve above that the pressures on both sides of the cylinder are identical for both models and it is obvious since the external load is identical on both.

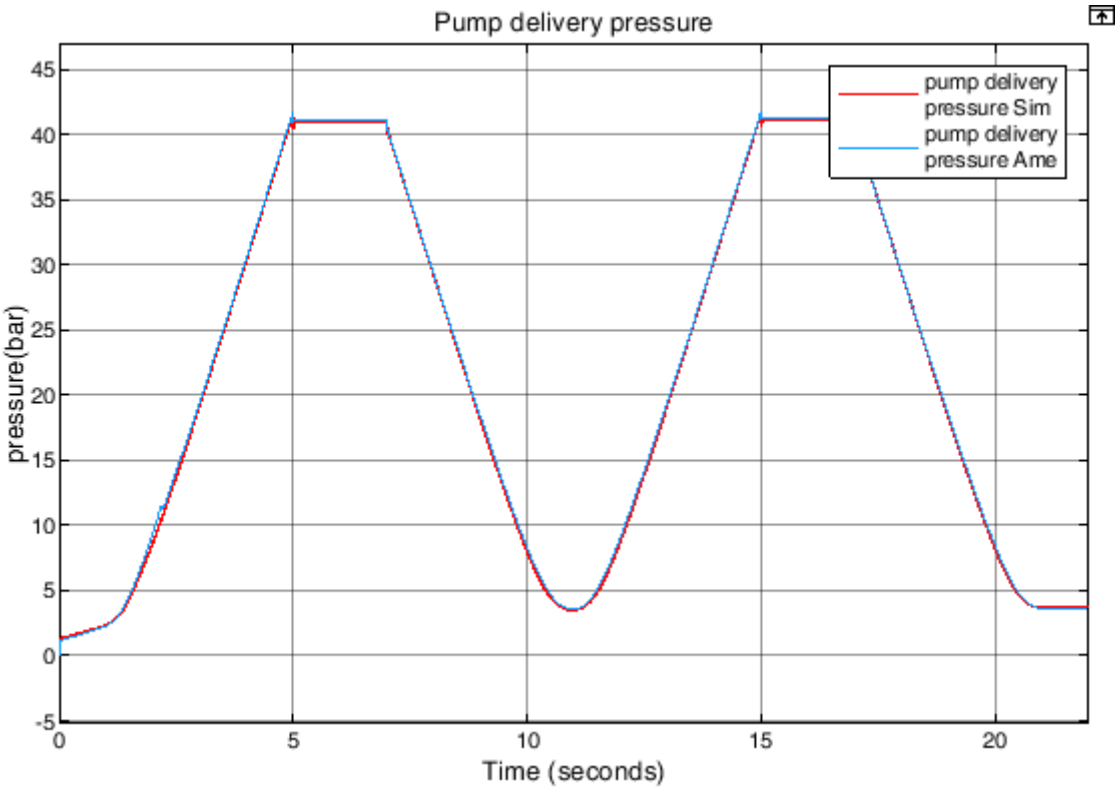


Figure 5-9 - pump delivery pressure

5.1.5 Steering Wheel Torque

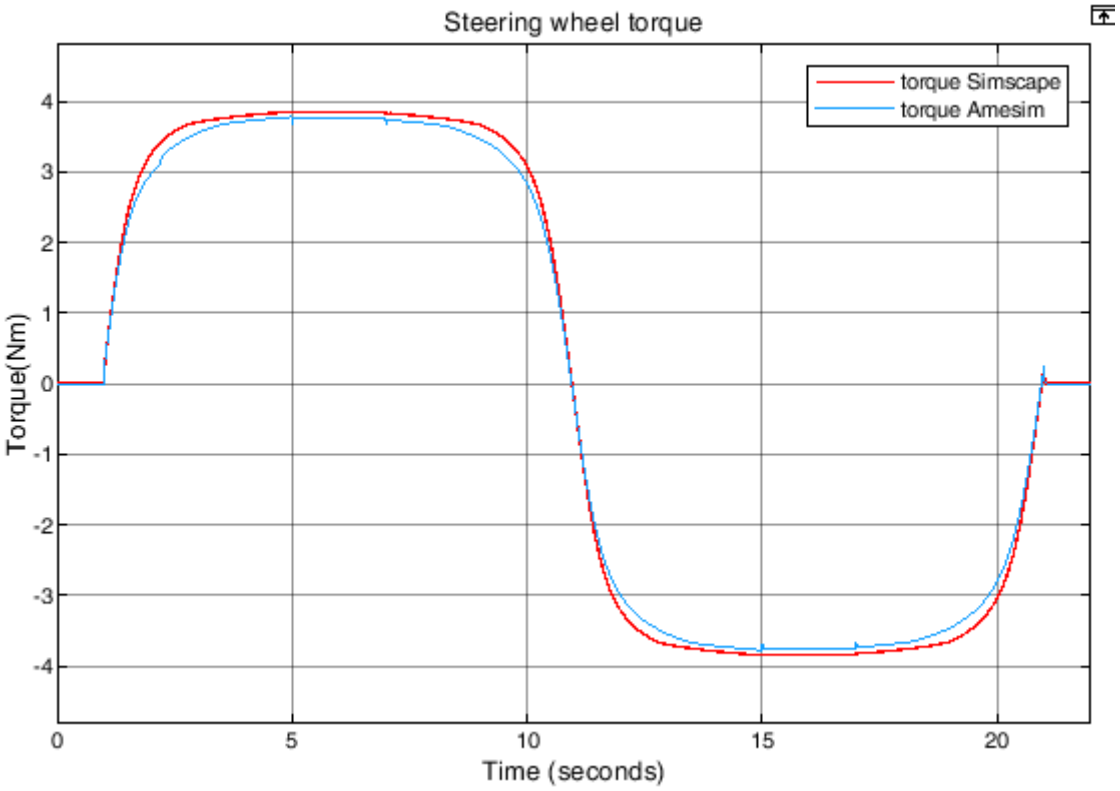


Figure 5-10 - Steering input torque

The figure above shows the steering input torque from the driver, the torque values are low as expected even though the external load is high, and this is due to the assistance to the steering manoeuvre done by the hydraulic part of the circuit hence the torque applied by the driver is that necessary to twist the torsion bar which is of relatively low stiffness.

Other curves can be obtained on Simscape varying the parameters in order to better visualise the functioning of some blocks. An example is seen on the following figure where the spring stiffness representing the external load is changed to 500000N/m. The pressure in the circuit rises above the relief valve pressure setting (82.82bar) and the relief valve opens to limit the pressure in the circuit by allowing a flow rate to pass through it back to the tank.

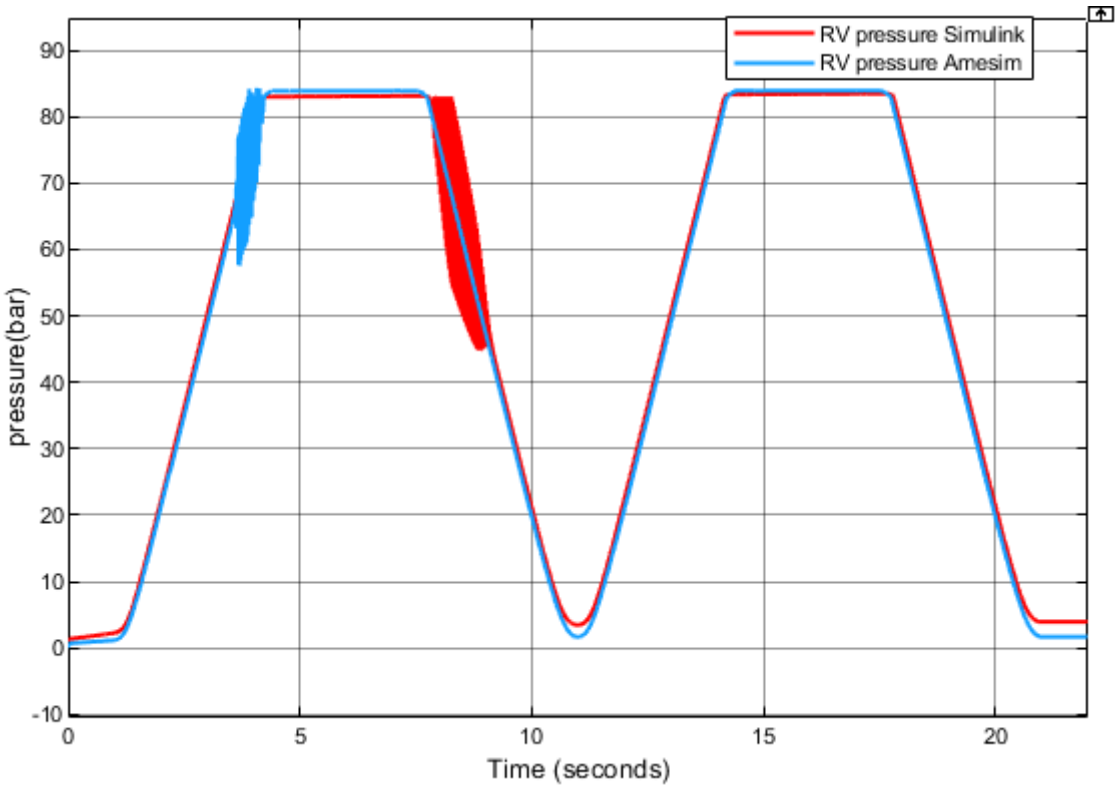


Figure 5-11 - pump delivery pressure with relief valve regulating

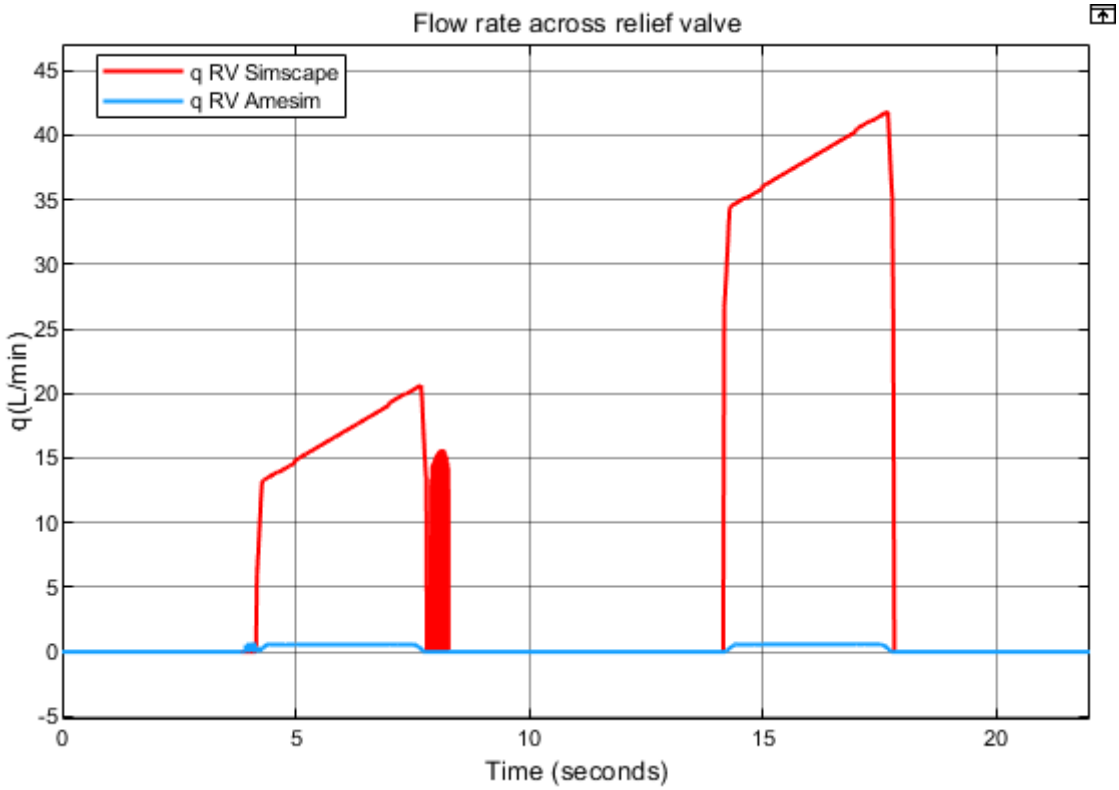


Figure 5-12 -flow rate across relief valve during regulation

It can be seen from the previous curves that the pressure upstream the relief valves are almost identical for both Amesim and Simscape. While the flow through the relief valves vary considerable from Amesim to Simscape. This is because the flow during regulation of the relief valve on the Amesim

model is a pilot flow i.e. a very small flow rate since the flow control valve used in this case is different from that used on Simscape in which a relief valve with a larger passage area in order to discharge the excess flow from the pump.

5.2 Amesim Vs Simscape Plots For Hydrostatic Transmissions

The characteristic plots for both Amesim and Simscape models are shown in this section. The Amesim plots are imported on Simulink and plotted together with their corresponding Simscape plots on the same scope to better highlight the differences.

5.2.1 Pump Flow Rate Curves

The first plots contrasted are the flow curves for the charge pump and the variable displacement pump.

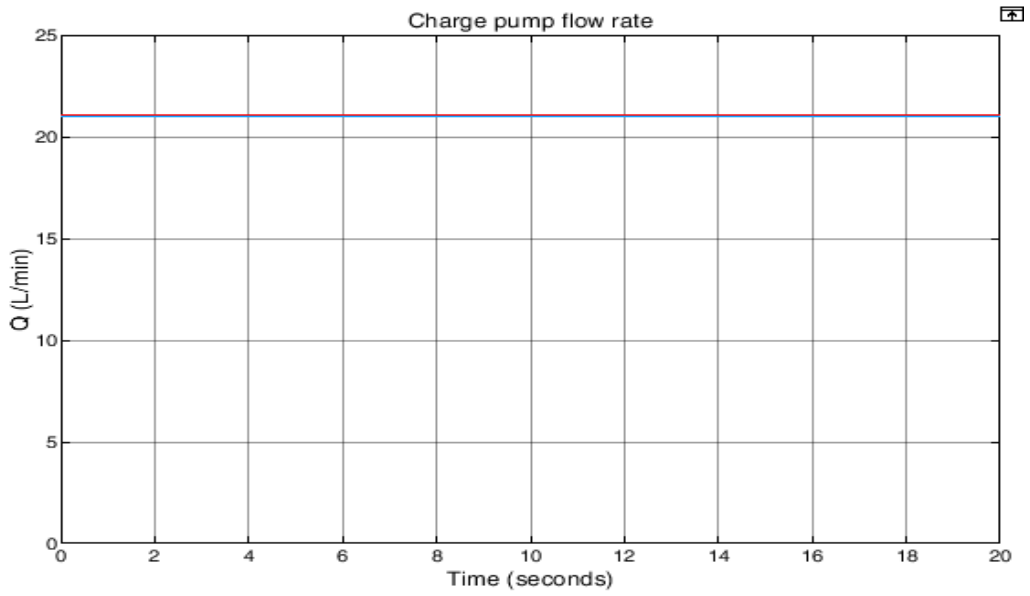


Figure 5-13 - Charge pump flow rate

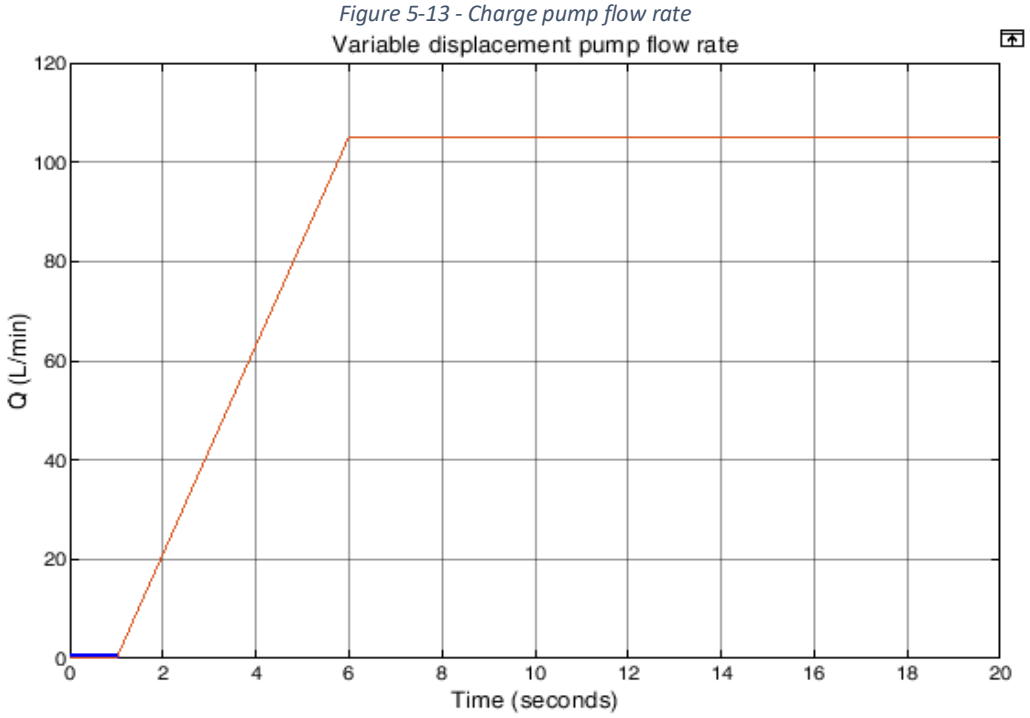


Figure 5-14 -Variable displacement pump flow rate

From the previous plots, the flow rates for the charge pump and the variable displacement pump are identical. This means that the flow rate supplied by the pumps on both models are equal.

5.2.2 External Load

Another important plot is the plot representing the load on both models which should also be equal.

Given these input flows and load the plot of the pressures on the high-pressure and low-pressure lines are compared.

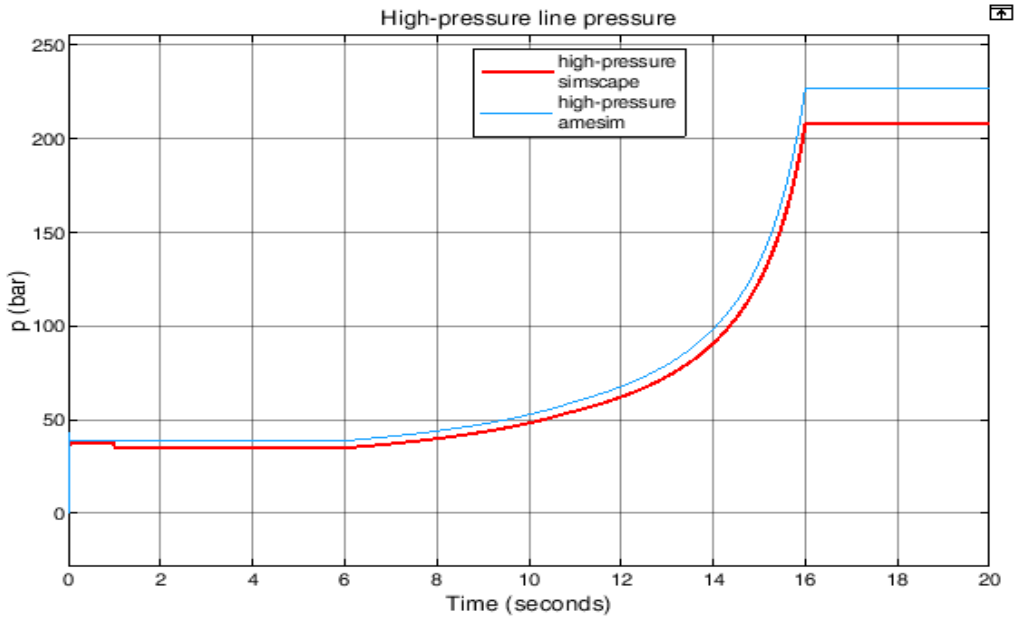


Figure 5-15 - High-pressure line pressure

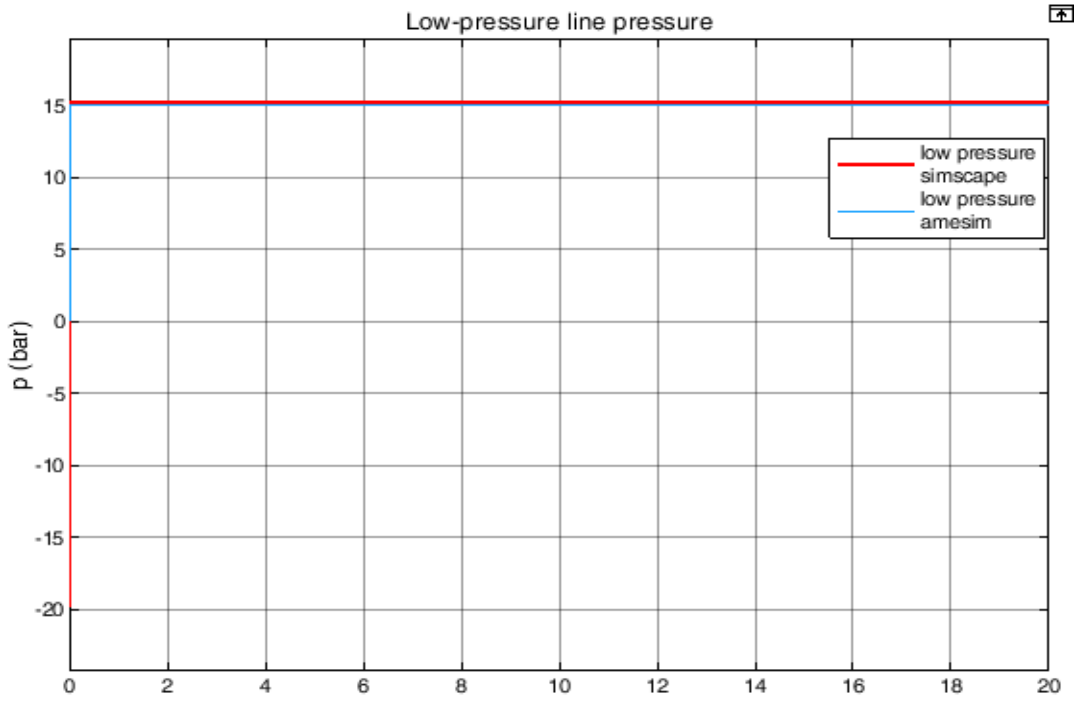


Figure 5-16 - low-pressure line pressure

The low-pressure line pressure is identical on both models but the high-pressure line pressures vary of about 10bars and is because the components used for both models have different parametrizations so the exact behaviours cannot behaviours for each component for the same input conditions.

5.2.3 Motor Speeds

The speed of Motor1 for both models are as follows.

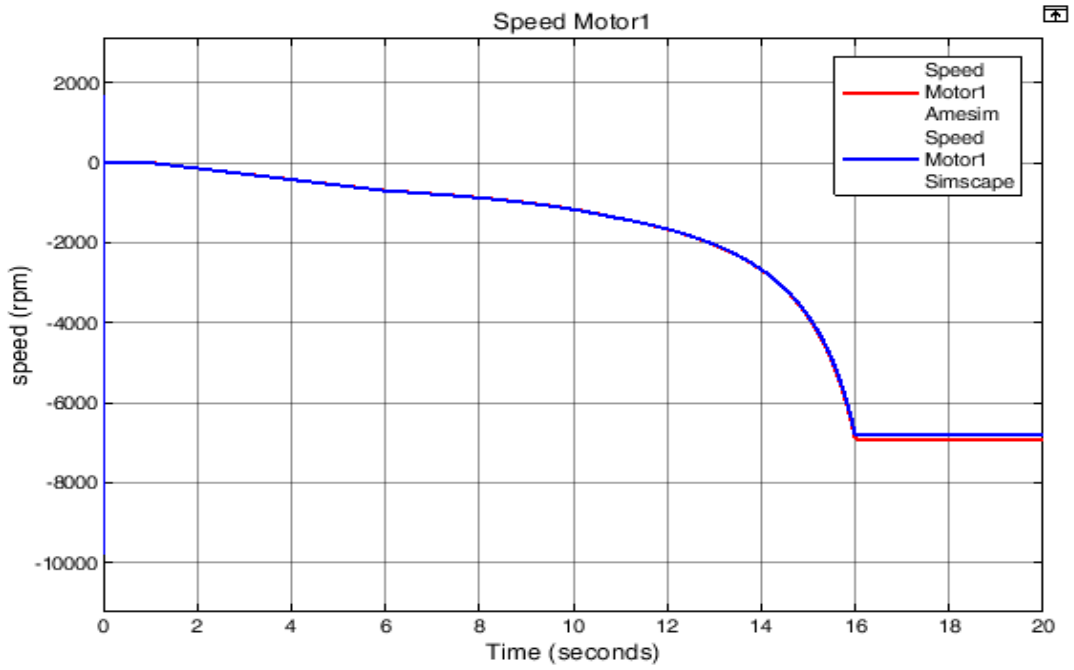


Figure 5-17 - Angular velocity motor1

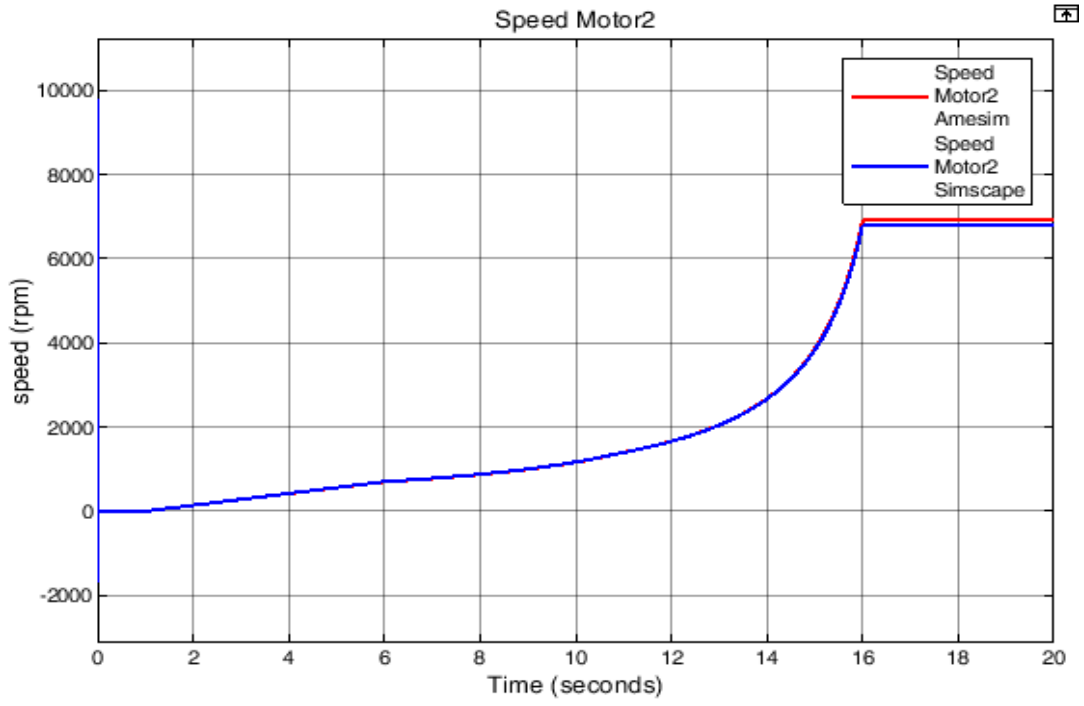


Figure 5-18 - Angular velocity Motor2

The rotational speed for both motors is equal as expected but vary slightly from Amesim to Simscape (123rpm) because of the slight difference between the pressure drops across the motors between the Amesim and Simscape models.

5.2.4 Flow Rate Across Motors

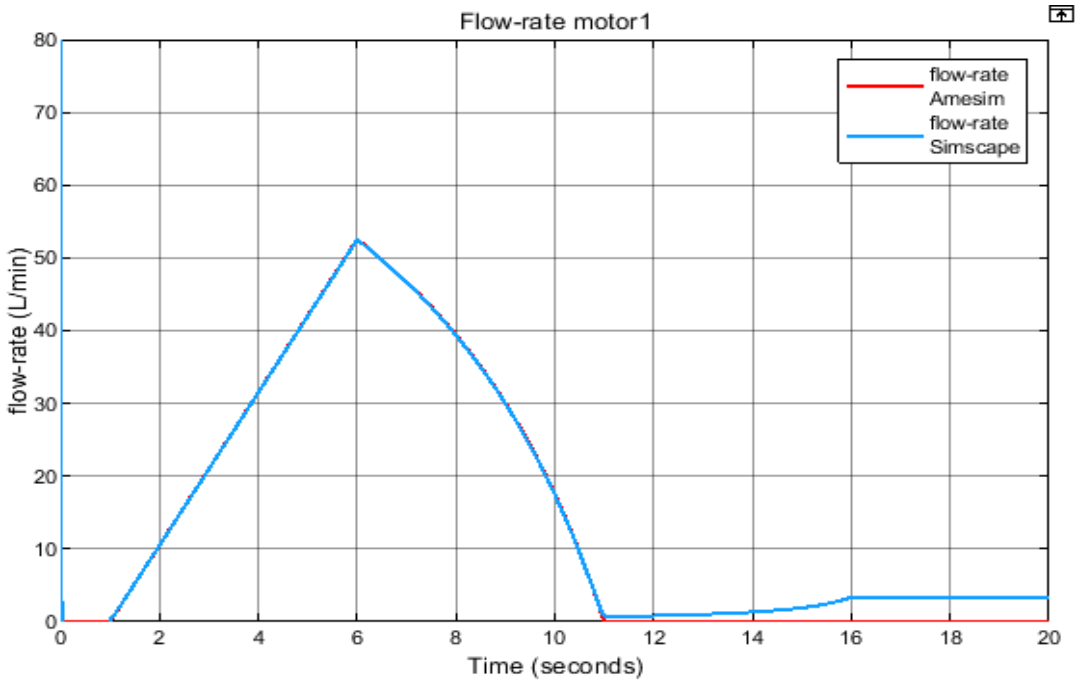


Figure 5-19 - flowrate across motor1

The previous figure show that the flowrate of the variable displacement motor1 is identical for both overlapping simulations until when the displacement modulation factor of motor1 goes to 0. There onward, the plots vary slightly with the flowrate of the motor1 slightly increasing compared to that of the Amesim simulation. This is because the variable displacement motors used on Simscape are not ideal i.e., the displacement of the motors cannot assume a zero value on Simscape.

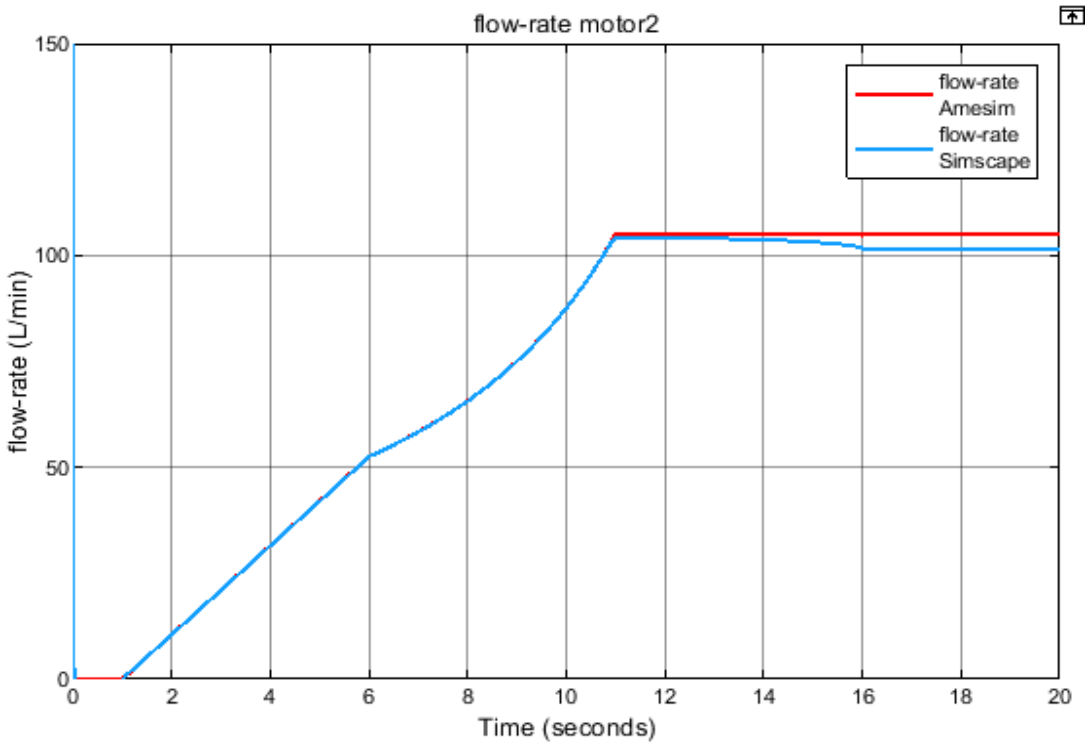
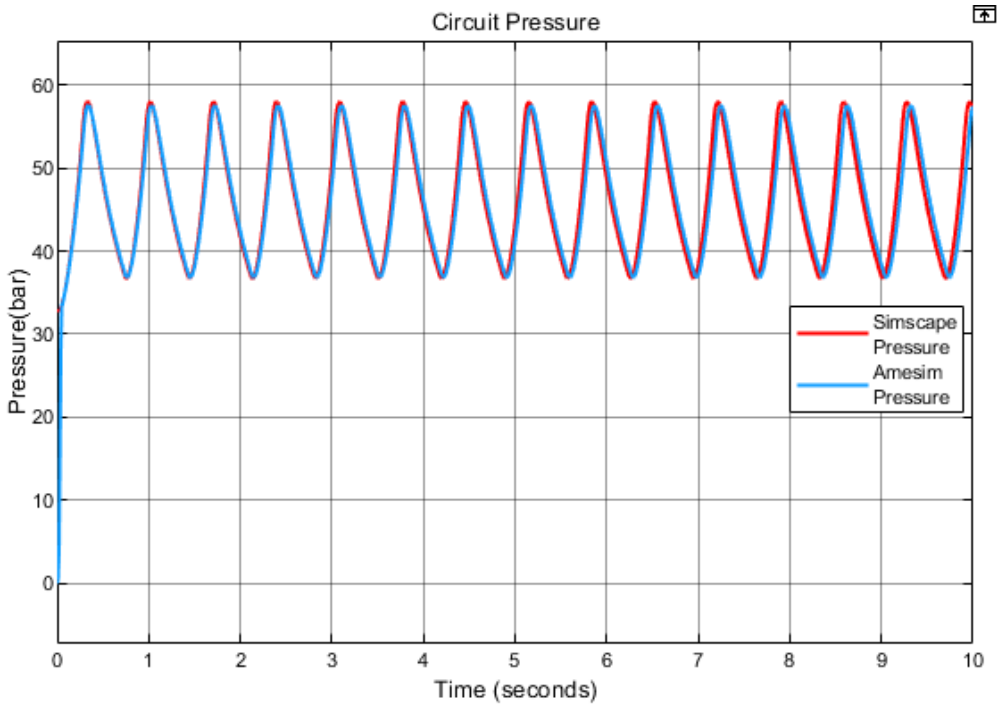


Figure 5-20 flowrate motor2

The flowrate of motor2 is overlapping for both models till when the displacement modulation factor of the motor 1 goes to 0. The flow above this point is not constant as it the case on the Amesim model because part of the flow still goes through motor1.

5.3 Amesim Vs Simscape Plots for Hydraulic Semi-Automatic Gearbox Control

5.3.1 Circuit pressure plot



The figure above shows the circuit pressure on both simulation platforms. The plots are almost completely overlapping and oscillate as expected it varies between the minimum (37bar) and maximum (55bar) values set on the model.

5.3.2 Pump flow rate

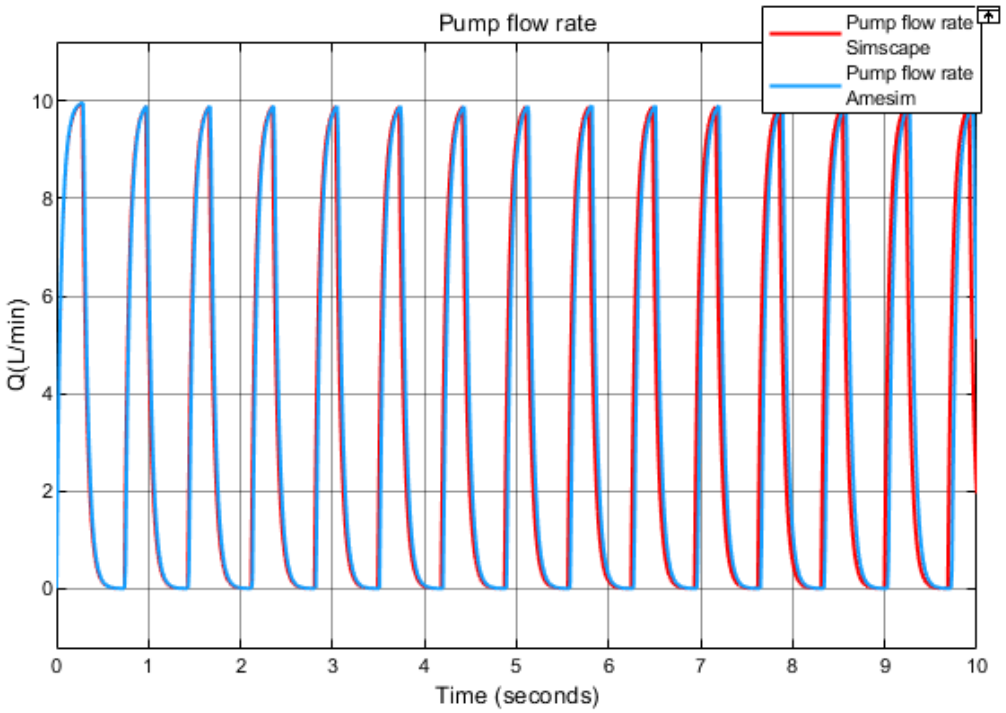


Figure 5-21 - Pump flow rate on both Amesim and Simscape models

The flow rate from the pump is almost overlapping for both models and is as expected i.e., oscillating because of the on/off signal from the pressure switch caused by the pressure oscillations in the circuit.

5.3.3 Accumulator flow rate

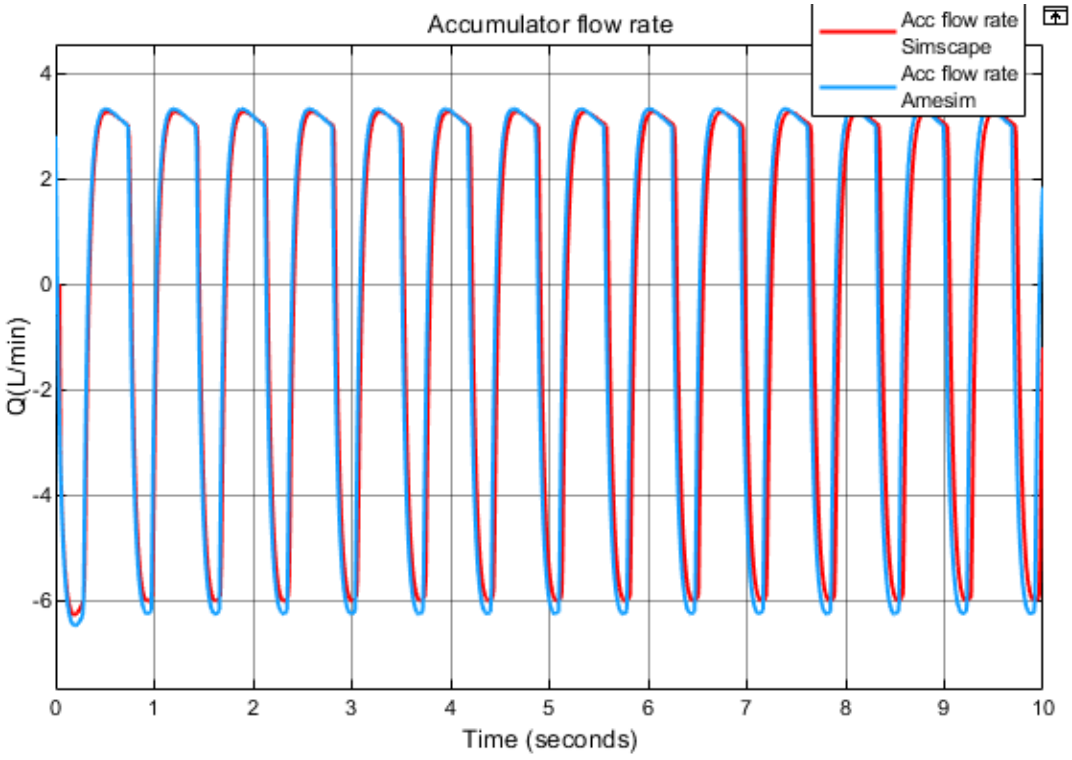


Figure 5-22 - Accumulator flow rate on Simscape and Amesim models

The flow rate oscillates as expected for both models but are not completely overlapping due to the different parametrizations on the component on both softwares for example flow area to the accumulator cannot be set on Simscape.

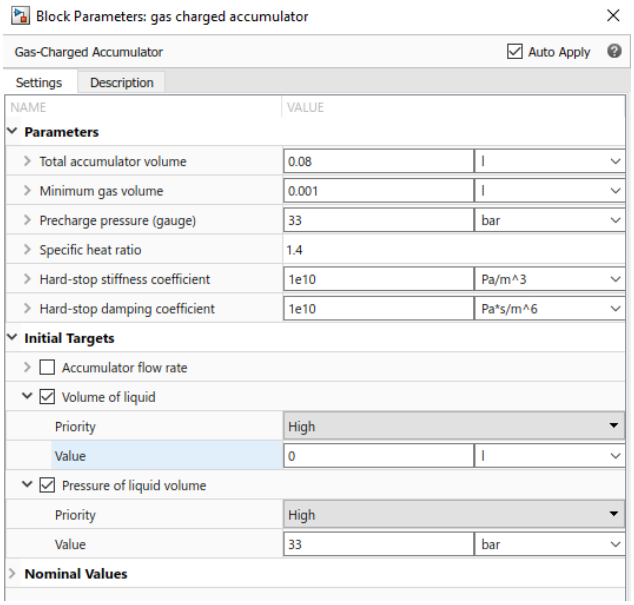


Figure 5-23 - Simscape accumulator settings

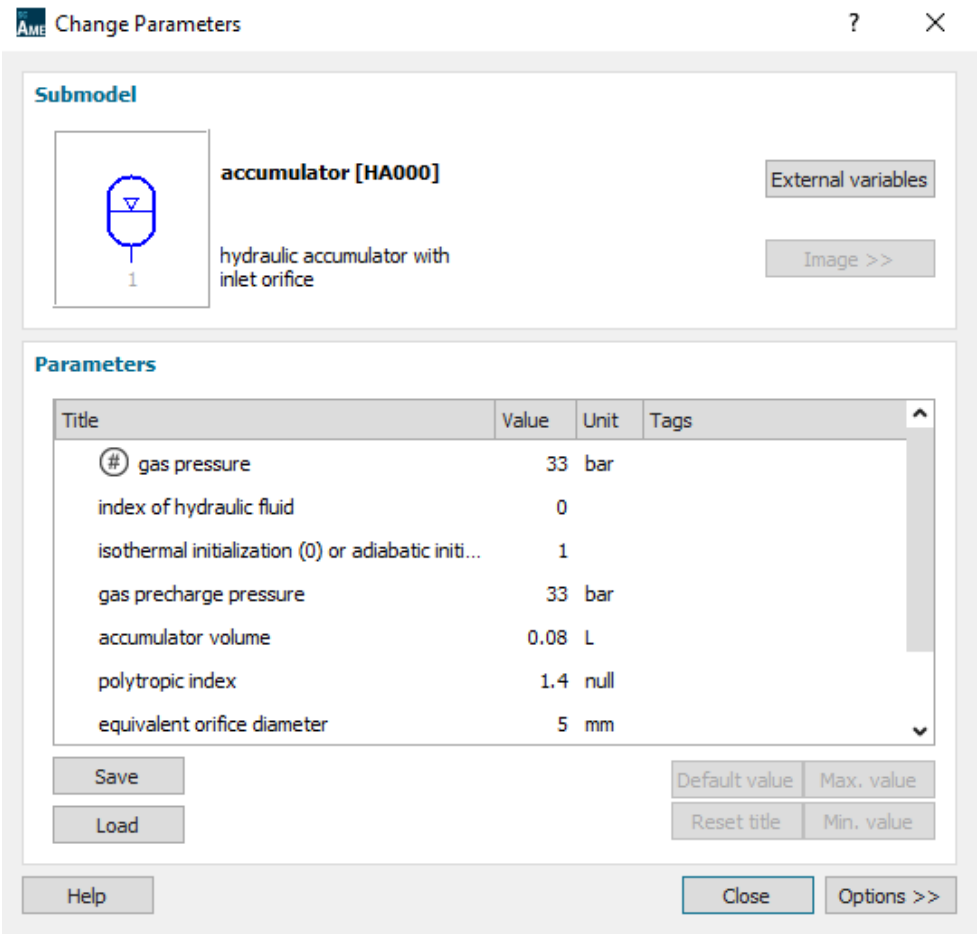


Figure 5-24 - Amesim accumulator settings

Another important simulation showing the functioning of the flow generation unit is done replacing the fixed area flow restrictor with a variable area flow restrictor. In this case an external signal commands the opening and closing of the flow restrictor.

Figure 5-25 - Variable area flow restrictor on Simscape

As shown on the figure above, the variable area flow restrictor is made of 3 ports. Input and output ports A and B, port S connects the block to the signal commanding its opening. The input signal S in interpreted as a stroke which commands the flow restrictor opening and closing.

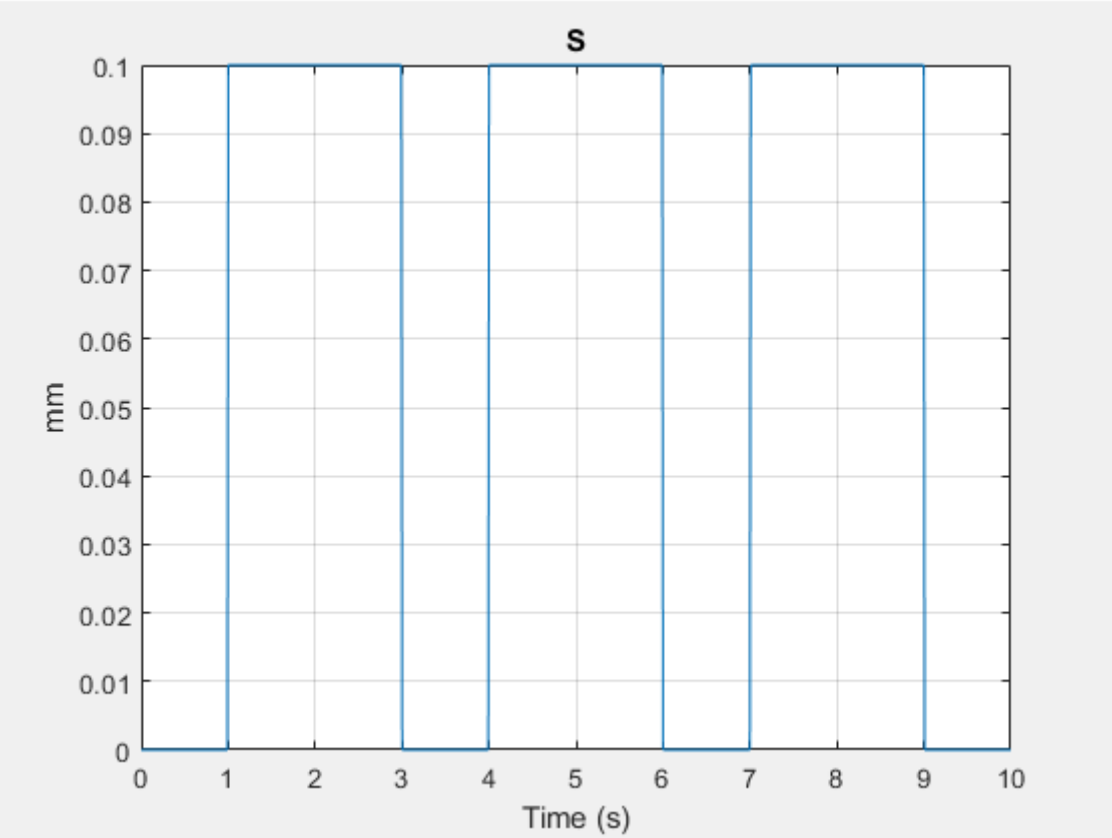


Figure 5-26 - input control signal for variable restrictor

It should be noted that a **0mm** stroke corresponds to a completely closed restrictor while a **0.1mm** stroke corresponds to a completely open restrictor with a passage area of **0.79mm.**

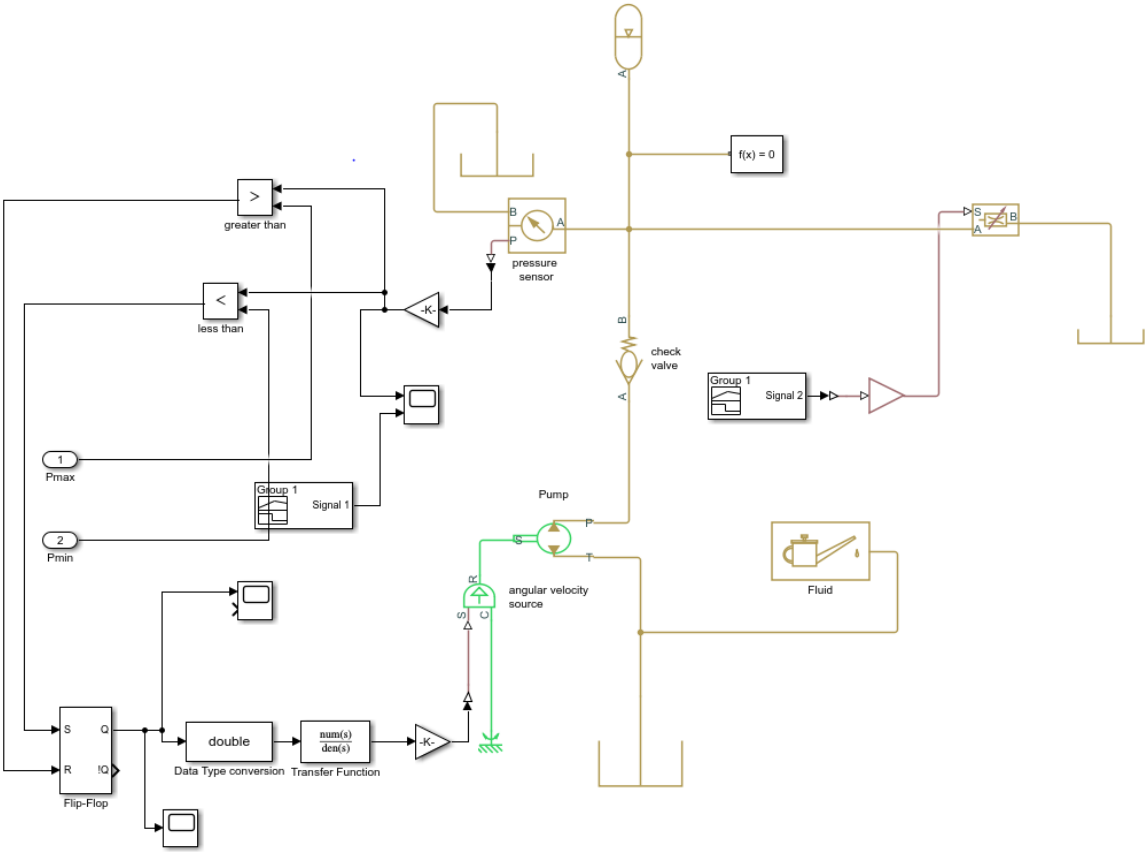


Figure 5-27 - Modified circuit with variable flow restrictor

The pressure in the circuit obtained for both models is shown on the following figure

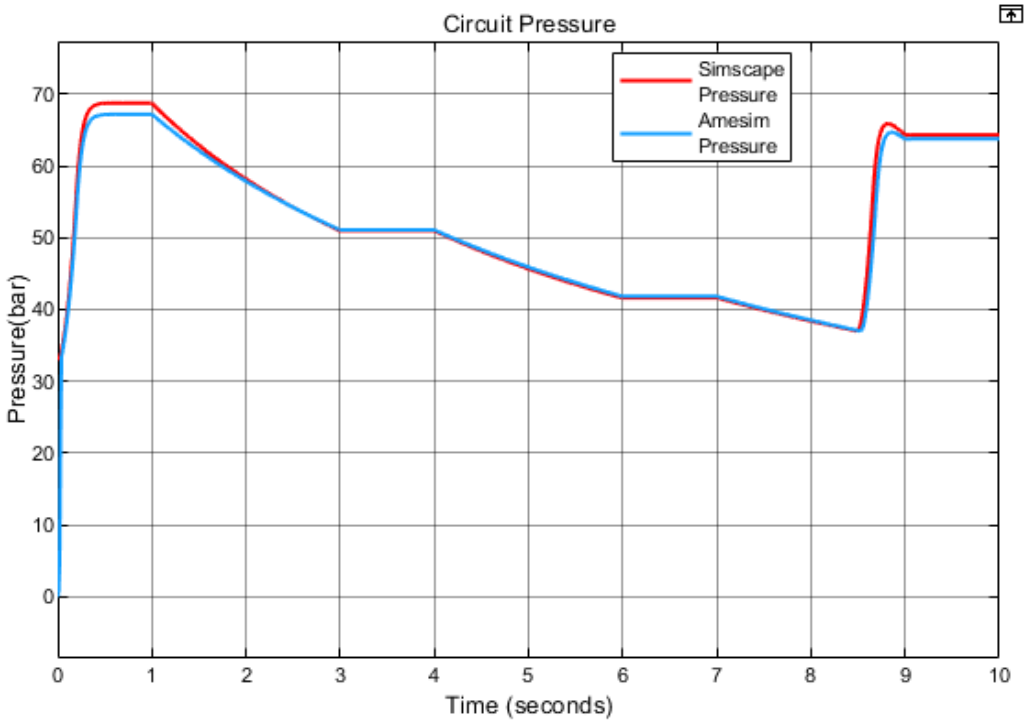


Figure 5-28 - Circuit pressure of modified circuits

The plots on the previous figure show a similar trend and behave as expected i.e., during the first second when the restrictor is completely closed, the pump charges the accumulator until the pressure in the circuit reaches the maximum value set on the switch then it stops. During the next two seconds, the restrictor is completely open and this causes a partial discharge of the accumulator reducing the pressure in the circuit. Two other complete closing and opening of the restrictor is done and this causes the pressure in the pressure in the circuit to continue dropping until it reaches the minimum value (37bar) set on the switch then the pump is reactivated and the pressure rises again.

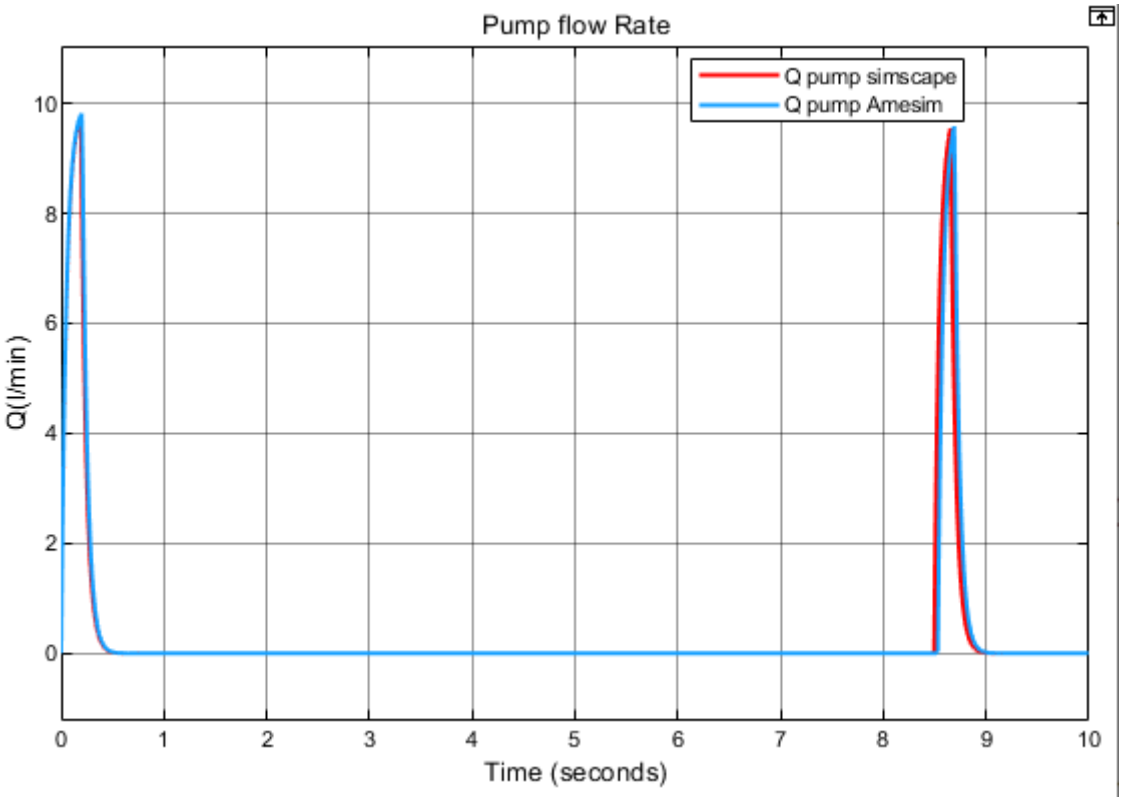


Figure 5-29 - Pump flow rate for modified circuits

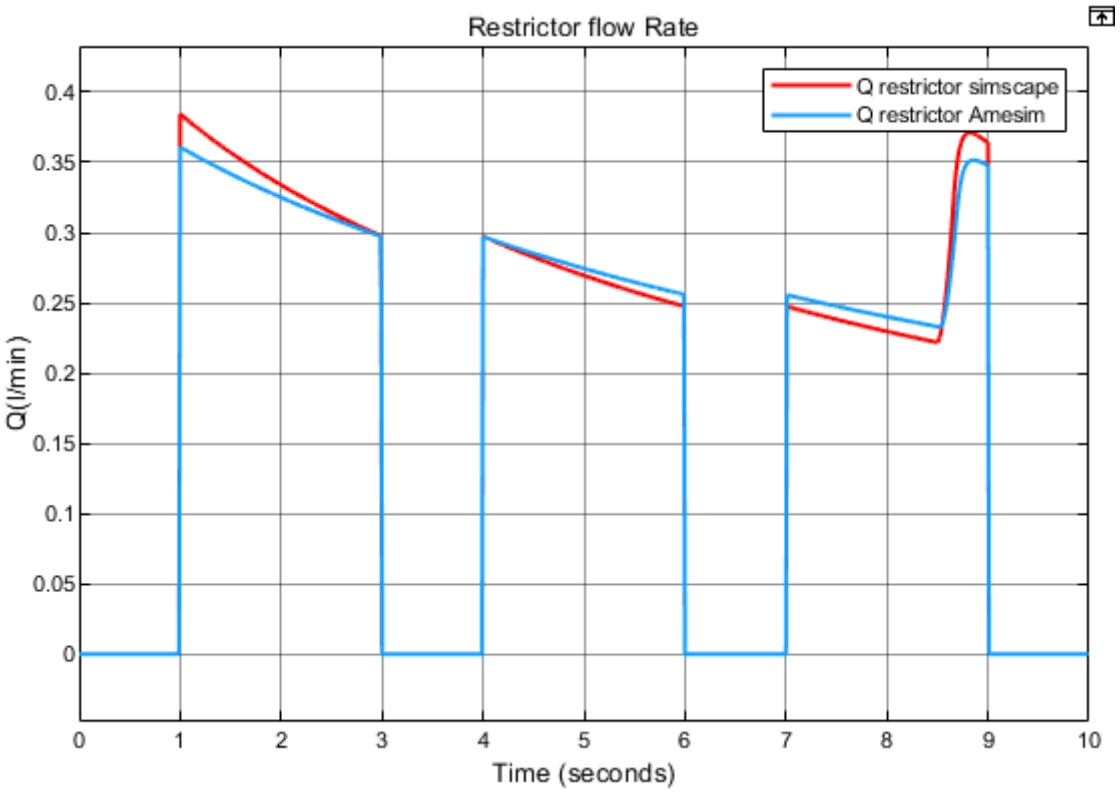


Figure 5-30 - Restrictor flow rates on modified circuits

The flow rate through the variable area restrictor is as expected i.e., gradually drop when completely open due to the pressure drop in the circuit caused by the discharge of the accumulator. The differences in the Amesim and Simscape plots are due to the passage area which are different on both models.

Chapter 6

CONCLUSIONS

In this section, the main differences, and similarities of both simulation softwares together with the main problems encountered reproducing the various models on Simulink are discussed.

6.1 Similarities between Amesim and Simscape

6.1.1 Icons of various hydraulic components and the connection between them

The icons of most of the hydraulic components are quite similar for both softwares. This makes the recognition of the various components easier. The connection between the various components is made in a similar way i.e., simply clicking on the ports of the components to be connected to one another.

6.1.2 Hydraulic fluids used for the various simulations

Simulink and Simscape offers a variety of hydraulic fluids (with standard parameters) that are readily available for use in the various simulations. They also both offer the possibility to use customized hydraulic fluids.

6.1.3 Simulation time

The simulation time for the various models studied in this case were quite similar on both sofwares so it can be said that the simulation time doesn't change much going from Amesim to Simscape but however the simulations become longer on Simscape when the parameters inserted for a certain component are not correct. This longer simulation times can also be an indicator for the correctness of a model on Simscape.

6.1.4 Signals

The signals needed as input for some components on both platforms can be obtained in similar ways i.e., using a signal builder in which it is possible to build custom signals or importing signal data from provided data sheets.

6.2 Differences between Amesim and Simscape

6.2.1 Parametrization

One of the main differences between both simulation environments is the parametrization of the various components. The same components often require different parameters on both softwares, this can be a problem when the data required by a component on Simscape cannot be obtained directly from the Amesim model or not readily available.

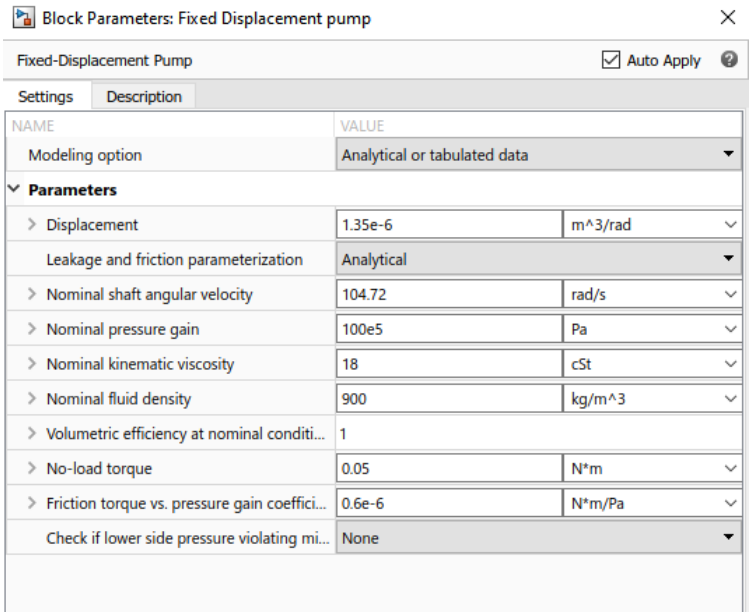


Figure 6-1 - Fixed displacement pump parameters on Simscape

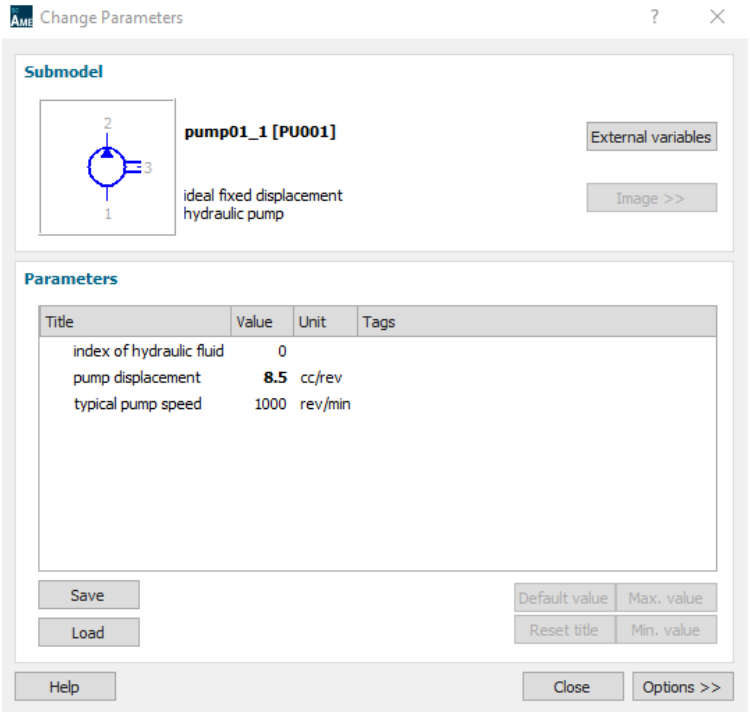


Figure 6-2 - Fixed displacement pump parameters Amesim

6.2.2 Non-customizable components on Simscape

Another very important difference to be noted is the non-ability to customize components (valves for example) on Simscape whereas it can be done on Amesim. This is a very big disadvantage of using Simscape because there is no degree of freedom on the various components to be used for the simulations and this limits the accuracy of simulations that could be done on Simscape.

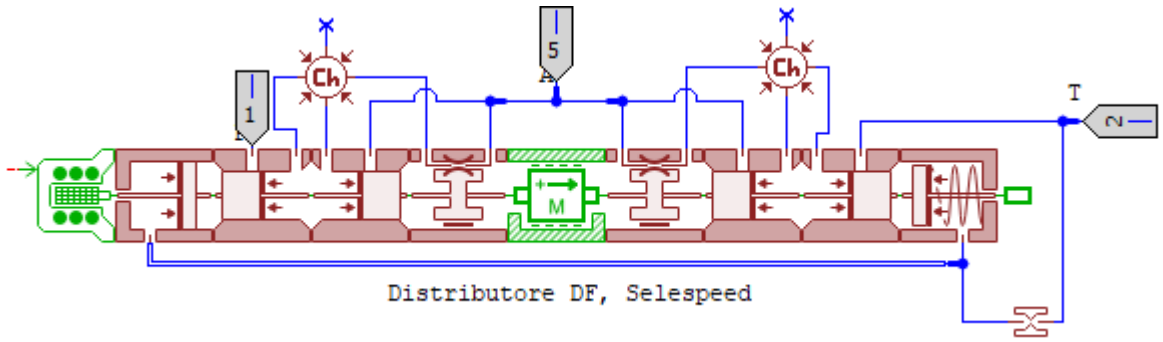


Figure 6-3 Example of a customized directional flow control valve on Amesim

6.2.3 Components present on Amesim which are not on Simscape

Several hydraulic components are not found on Simscape e.g., **RQ3 flow regulation valve**, **solenoid actuated directional control valves** etc. This greatly influences the type of simulations that can be done on Simscape. It should also be noted that most Simulink hydraulic components implicitly consider losses this makes it difficult to simulate ideal working conditions.

6.2.4 Post-processing

Simulation post-processing on Amesim is quite easy since the plots are done simply from a drag and drop command of the variable to be plotted from the result dialog box of the component. Several variables can be plotted on the same graph with the same drag and drop command this makes post-processing of simulation data less time consuming.

On the other hand, post-processing is not obvious on Simscape. Simulation output data and plots are obtained on Simscape either by connecting scope to a sensor connected to the circuit which measures the variable needed or by logging the complete simulation data to a folder where all the variables for all the components can be obtained after the simulation is completed. To critically compare two variables on Simscape, the simulation data must be exported on Matlab and plotted using simple Matlab codes.

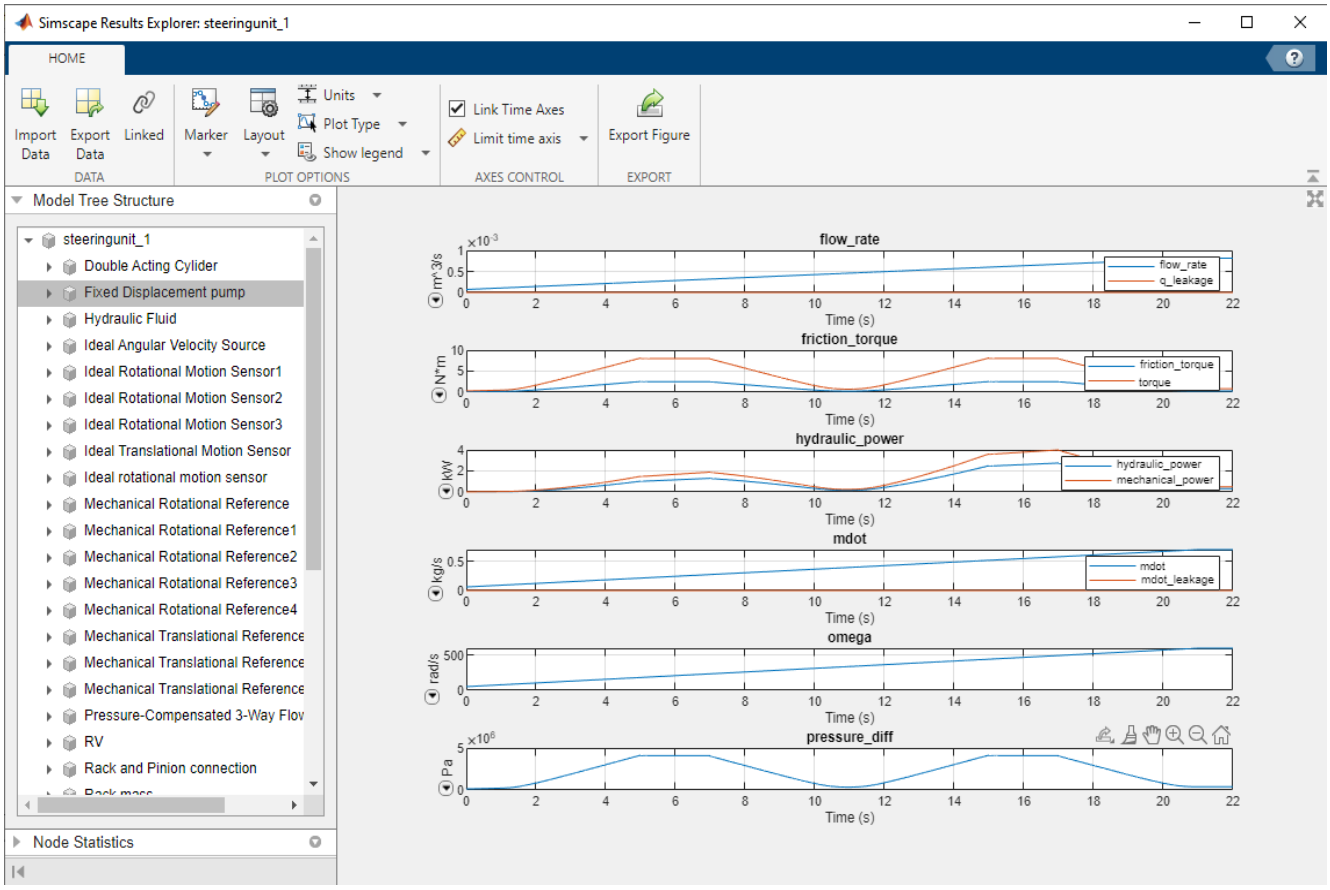


Figure 6-4 - Exampled of simulation output data on Simscape

Finally, what could be said after this work is that Simscape Fluids can be used to simulate not so complex models yielding good, accurate and reliable results even if a good knowledge of its usage is required to properly carry out the various operations while more complex simulations should be carried on Amesim to have reliable results and also for time saving.

ACKNOWLEDGMENTS

This work was a quite challenging one having to go from scratch learning how to use both simulation platforms, but this enabled me to learn much during this process and I am very satisfied with the outcome of this thesis. That said I would like to thank above all the almighty God for giving the strength during these years to face the challenges encountered during my university career, my family who is always there for me, my supervisor who was always readily available for assistance, my friends who kept me going all the way and everybody who assisted me during this journey. Thank you once again.