Analysis of an hydraulic switching converter with analog hysteresis feedback control

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Summary. Hydraulic switching converters control a hydraulic state, such as pressure or flow rate, by the frequent switching of on-off valves in combination with some hydraulic inductance element and means to flatten pulsation due to switching. In nearly all modern versions of such converters the switching is provoked by electrically actuated valves. The historically first of such converters, Montgolfier's hydraulic ram, used a hydraulic feedback mechanism, because of lacking electrically controlled valves in his time. To make use of the significant cost advantage of pure hydraulic control, authors studied a concept for a buck converter for pressure control based on a specific feedback mechanism. In a theoretical analysis it turned out that this system exhibits a clustering of switching activities in certain operation domains which causes a bad pressure control performance. This paper analyses the essential inner mechanisms responsible for the operational performance and shows how to efficiently calculate approximate stability bounds in state space by using reduction methods.

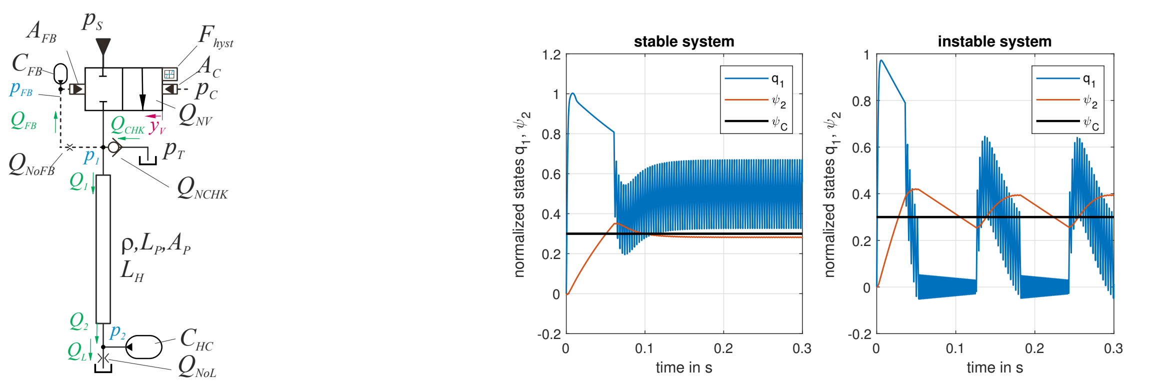
Introduction

Fig. 1a shows the schematic of the hydraulically controlled buck converter as presented in [1]. An hydraulic inductance pipe L_H is actively switched to system pressure line p_S by a hydraulically piloted 2-2 way on-off valve. During off-phases a fast check valve opens due to oil inertia and the pipe is connected to pressure line p_T. The hydraulic capacitance C_{HC} flattens pressure and flow pulsation at the convert's output. The control principle employs feedback of a low-passed filtered version of p_1 via a feedback circuit (orifice Q_{NoFN}, capacitance C_{FB}) which counteracts as force $p_{FB}A_{FB}$ against the control force $p_C AC$. This mechanism targets controlling the time mean of pressure p_1 at the pipe entrance which is expected to approximate the mean system output pressure p_2. In order to assure a fast switching, when p_{FB} exceeds or falls below the threshold values, a hysteretic force F_{hyst} is realized by a special element. A feasible hydraulic design as well as the investigation of a detailed numerical model is presented in [1].
An impression of the converter's control performance and dynamical properties for different operating conditions is given by the diagrams in Fig. 1b. The response on the left hand side meets the main expectations and the desired output pressure $p_2 = p_C$ is reached after a rise time of approx. 0.1 seconds. The right hand side case with a low demanded pressure and a small flow rate, however, show an unacceptable behavior in form of clustered switching which leads to a bad control performance. The understanding of this behavior, i.e. of the essential inner mechanisms and the influence of the main system parameters, is the objective of this paper. This is achieved by model reduction and using the averaging method.

Modelling

The study of the dynamical properties is based on a simple model which incorporates pressure build-up equations in the hydraulic capacitances in node 1, FB and 2, oil inertia an the corresponding change in flow through the hydraulic inductance pipe, as well as orifice equations through the 2-2 way valve, the check valve and the throttle in the feedback circuit, resulting in a system of equations in nondimensionalized form

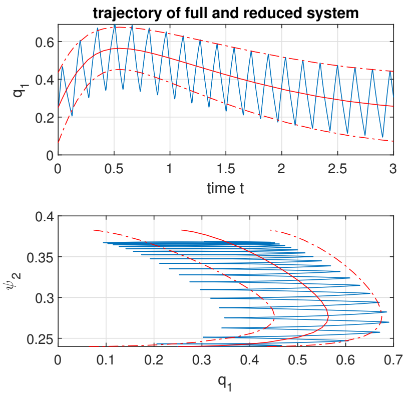
$$\frac{d}{dt}\begin{pmatrix}\psi_{FB}\\ \psi_1\\ \psi_2\\ q_1\end{pmatrix} = \begin{pmatrix}\sqrt{\psi_1-\psi_{FB}}\\ a_{NV}\left[q_{NT}H(\psi_T-\psi_1)\sqrt{\psi_T-\psi_1}+y_{Vrel}\sqrt{1-\psi_1}-q_1\right]\\ a_{HL}(q_1-q_L)\\ -r_H q_1+\frac{1}{l_H}(\psi_1-\psi_2)\end{pmatrix}. \tag{1}$$



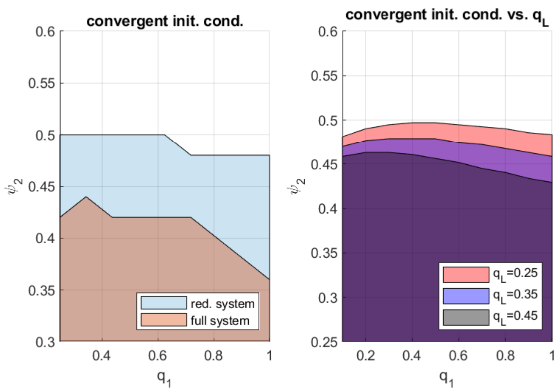
(a) Greatest figure of all time

(b) Stable and instable system behavior for different parameter sets.

Figure 1: Schematic of hydraulic buck converter and corresponding system behavior.



(a) Comparison between full and reduced system.



(b) Convergent set of full and reduced system (left). Convergent set of red. system for different values q_L (right).

Figure 2: Simulation results

The main valve and check valve dynamics are disregarded and infinite fast switching is assumed. This is already considered for the check valve in the orifice equation by introducing the heaviside function $H(\cdot)$ in the pressure built-up equation for ψ_1. The discrete state dynamics of the main valve is modeled by the variable $y_{Vrel} \in \{0,1\}$ which changes infinitely fast from $0 \to 1$ and from $1 \to 0$ when $\psi_{FB} \gtrless \psi_C \pm \psi_{hyst}/2$.
Eq. (1) describes a non-linear switched system with dynamics on two different time scales, one is the switching of the valve which introduces high-frequency components and the other is the system's internal dynamics. Interestingly, this system is unstable for certain initial conditions, i.e. for a certain parameter set the locally stable system can get unstable if the initial conditions are chosen badly. Solving system (1) for various different combinations of parameters and initial conditions gets inefficient as one has to initialize the solver whenever the state of y_{Vrel} which depend on the fast time scale changes. Therefore, a smooth approximation for the system was derived.
First, the size of the capacitance at node 1 which corresponds to the inverse of parameter a_{NV} is assumed to be very small. This results in a singular perturbed equation as $1/a_{NV}\dot{\psi}_1 \to 0$, which gives a quadratic expression for ψ_1 for both states of y_{Vrel}. Secondly, the equation for the feedback pressure ψ_{FB} has approximately triangular waveform and so the state-dependent duty cylce $\alpha = fT_{on}$ and the state-dependent pulse-width modulation frequency f can be calculated. The remaining two-dimensional system of equations can be further approximated by using the method of averaging [2]. By introducing the time transformation $t = \epsilon\tau$ one obtains the two-dimensional system in standard form $\dot{x} = \epsilon f(x,t) + \epsilon^2 f^{[2]}(x,\epsilon)$ which can be approximated by a two-dimensional averaged system

$$\frac{d}{dt}\begin{pmatrix}\bar{\psi_2}\\ \bar{q_1}\end{pmatrix} = \begin{pmatrix} a_{HL}(\bar{q_1} - \bar{q_L}) \\ -r_H\bar{q_1} + \frac{1}{l_H}(\psi_T - \frac{\bar{q_1}^2}{q_{NT}^2} + \alpha(\bar{q_1})(1 - \bar{q_1}^2 - \psi_T + \frac{\bar{q_1}^2}{q_{NT}^2}) - \bar{\psi_2})\end{pmatrix}. \tag{2}$$

with only four remaining parameters and a smooth right-hand side. This system is used to calculate approximate convergent sets. A physical explanation for the system to get unstable is a oil flow from the output in the backwards direction. Such a flow immediately increases the pressure ψ_1 in node 1 as its capacitance is very small. This pressure is fed back to the main valve demanding for the valve to close. Since only a positive oil flow q_1 (which opens the check valve to the tank) can decrease pressure ψ_1 the controller does not exhibit the intended behavior. The backwards oil flow is due to the system's internal dynamics (long time scale) which is approximated by the reduced two dimensional system reasonably well. For the complete system the condition for getting unstable is $q_1 < 0$. To the averaged system $\bar{q_1}$ to approximate the minimum of q_1 an expression for the ripple must be subtracted. The first order approximation of the ripple is $\Delta_q = T_1(1 - \bar{q_1}^2 - \psi_C)/l_H$. Fig. 2a shows a solution of the complete and the approximated system. The diagrams in Fig. 2b show true and approximate bounds of a convergent set of initial conditions and the such a converging set for different loading q_L which was calculated by using the reduced system.

Conclusions

A hydraulic buck converter was modeled by a nonlinear switched system. It shows to have bounded regions in state space which are locally stable. To efficiently compute the bounds for different parameters a reduced system with smooth right-hand side was derived and approximations of the stable regions were calculated.

References

[1] Scheidl R. (2021) Hydraulic Control of a Buck Converter. Proceedings of the ASME 2019 ASME/BATH Symposium on Fluid Power and Motion Control, FPMC 2021.

[2] Calvente, Javier, Abdelali El Aroudi, Roberto Giral, Angel Cid-Pastor, Enric Vidal-Idiarte, and Luis Martínez-Salamero. (2018). Design of Current Programmed Switching Converters Using Sliding-Mode Control Theory, Energies 11, no. 8: 2034.