Analysis and control of a complementary energy recuperation system

M. Sc. Karl Pettersson

Division of Fluid and Mechatronic Systems, Linköping University, SE-581 83 Linköping, Sweden, E-Mail: karl.pettersson@liu.se

Tekn. Lic., M. Sc. K. Heybroek

Volvo Construction Equipment AB, SE-631 85 Eskilstuna, Sweden,
E-mail: kim.heybroek@volvo.com

M.Sc. Andreas Klintemyr

Division of Fluid and Mechatronic Systems, Linköping University, SE-581 83 Linköping, Sweden, E-Mail: andkl591@student.liu.se

Prof. Petter Krus

Division of Fluid and Mechatronic Systems, Linköping University, SE-581 83 Linköping, Sweden,
E-Mail: petter.krus@liu.se

Abstract

In recent years, hybrid technologies have been in focus in both industry and academia. This paper deals with a hydraulically connected energy storage system based on a two-machine hydraulic transformer. Connecting the energy storage system hydraulically enables easy disconnection and possibly fewer power domain transformations than with the conventional mechanically connected parallel hybrid structure. The control feasibility and different control aspects are investigated and a control strategy is proposed. The control strategy is based on linear control techniques and it is shown that even with simple models of the system, sufficient control performance can be achieved.

KEYWORDS: Parallel Hybrid, Hydraulic Transformer, Energy Recuperation, LQ Control

1. Introduction

Over the past decade the development of hybrid technologies has been a huge trend in the automotive industry. Parallel hybrids are of special interest in this study since they normally require few modifications to the host system. **Figure 1** illustrates a stylized overview of the motion control system of a large construction or mining machine. It also shows all the possible connecting nodes for a parallel energy storage system (ESS), irrespective of physical domain. In the example, two loads are present; one translational mechanical and one rotational mechanical. The power transmission from the primary mover to the loads goes via mechanics, hydraulics and electrics. In this study, the hydraulic connection node is of greatest interest. Relative to a mechanical connection where cogs and gear-

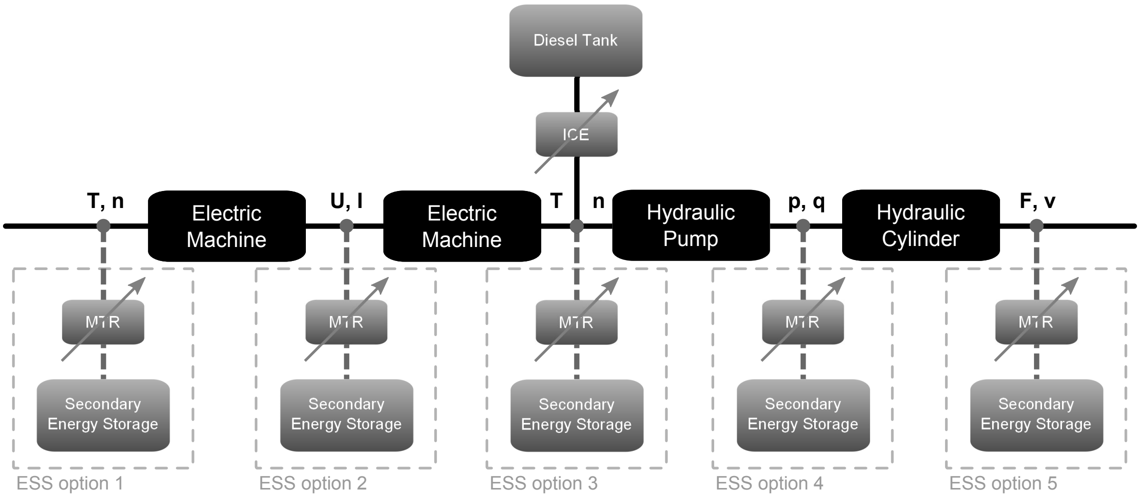


Figure 1: A stylized representation of a construction machine, demonstrating all possible connection nodes for a secondary energy storage system considering all possible domains present in the machine architecture.

boxes must be used to branch out power, the hydraulic connection only requires a very simple T-pipe junction. In the mechanical case, the traditional way to achieve a parallel hybrid is to let the rotating shaft drive a, by some means controllable, hydraulic or electric machine (in the figure called a modulated transformer, MTR). The implication with this solution is that the MTR always rotates along with the shaft, causing drag losses even when the hybrid system is not in use, unless a clutch is introduced. In a hydraulic T-pipe junction on the other hand, the intensities (pressures) are equal in all branches and the flows are instead summed together. A hydraulic connection is also easy to disconnect with simple valves on the hydraulic lines. Furthermore, power transmission over hoses and pipes is very flexible in hydraulics, allowing for dispersal and even several connection nodes. Moreover, the hydraulic connection node could in some cases create a shorter chain of domain transformations relative to its mechanical equivalence.

2. System Proposal

In this study, a parallel ESS is proposed, using a hydraulic transformer and an accumulator as energy storage device. The power transformation takes place using two independently variable piston type hydraulic machines on a common shaft. This configuration is then connected to the host system with a hydraulic connection point, see **Figure 2**. The idea of transforming hydraulic energy via the mechanical domain is nothing new. Already in the early 80's significant research was done on exactly the same concept /1/, /2/. From the late 90's up until today much research was done on alternative transformer principles where one machine may be used instead of two in an endeavour to make the component more energy efficient and commercially viable, see /3/ and /4/. Linear switching hydro-mechanical transformers have also been investigated /5/. Another option is to perform

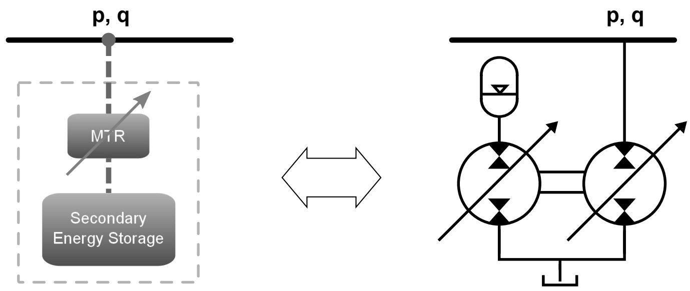
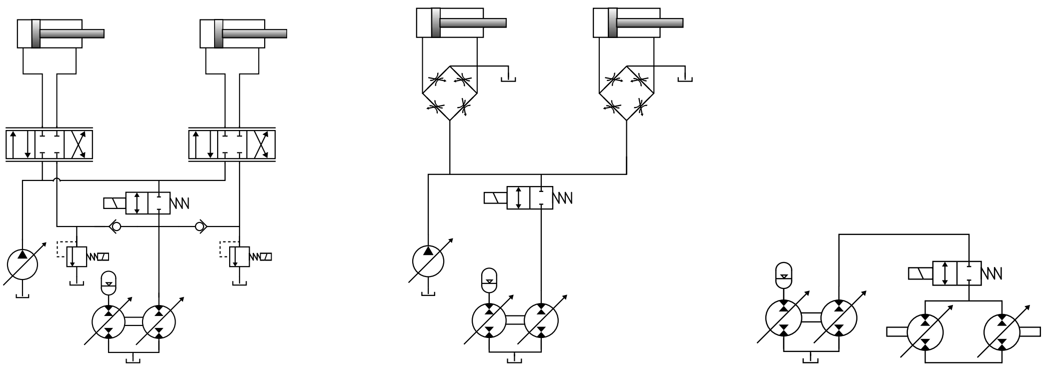


Figure 2: The hydro-mechanical transformer connected to a hydraulic node in the host system power flow, hence having a parallel structure.

the transformation within the hydraulic domain /6/. Coming back to the idea of having the ESS connected in a parallel structure; one clear advantage is that the solution requires only very little modification of the host system. **Figure 3** shows some examples how this system may complement a standard hydraulic system. Similar solutions may also be



(a) An ordinary valve controlled system.

(b) A pump controlled system using individual metering valves.

(c) A hydrostatic transmission.

Figure 3: Examples of how the complementary energy recuperation system may be connected to standard hydraulic systems.

found in previous research, for instance /7/, /8/ and /9/. This type of system enables potential or kinetic energy to be recuperated from both linear and rotary loads, transforming the hydraulic power of the actuators to the accumulator. When the system is not in use, the hydraulic transformer may stand still. The system is simply disconnected by means of on/off valves. Moreover, the rotational speed of the transformer is not determined by the prime mover and therefore allows a greater conversion range compared to the traditional mechanically connected parallel hybrid system.

3. Control Strategy

The potential of the proposed ESS very much lies in its ability to handle the power transformation between the host system and the energy storage. Due to its physical properties, the two-machine transformer is very challenging to control. The system is a MISO

(Multiple Input-Single Output) system, with the machine displacements as input and the load flow to the host system as output. It is also necessary to keep a suitable angular velocity of the transformer to avoid overspeeding and stick-slip effects at low speeds. The cross-couplings of the machine displacements, however, cause difficulties to intuitively build controllers in order to satisfy these demands. The system is also very stiff, with a small inertia which causes the system to be very sensitive to disturbances and pressure variations. There are also strong non-linearities, such as a high stiction torque of the machines acting during stand-still and at low angular speeds. This effect is particularly influential due to the low inertia, causing rapid accelerations and decelerations when rotating close to zero speed, see also /4/. The objective of the control design in this paper is to achieve a fairly simple and robust controller which is not necessarily optimal, but sufficient for implementation in a real application. The control synthesis focuses on the control strategy when the transformer is in motion rather than the problems associated with starting and stopping.

For controller design, linearisation techniques are used in order to keep the controller simple and robust. By looking at several linearisation points, it is possible to observe the influence certain variables have on the systems behavior. With this information, an adaptive controller can be applied to match the non-linear effects. An example of such a study is /10/, where the author studies the dynamics of a hydrostatic transmission and applies gain-scheduling laws to achieve a more robust behavior of the closed loop system. Previous research on the control of hydraulic transformers can be found in /4/, in which a system with a one-machine transformer controls the position of a cylinder. The suggested controller uses a model-based estimator (feed forward) based on the surrounding pressures and the angular speed of the transformer. This is combined with a simple PI-feedback to avoid static errors and achieve a better dynamic behavior. Wei /11/ studied similar energy recuperation systems, using a hydraulic transformer connected to an accumulator. The suggested controller design decoupled the two machine displacements by using one control loop with the objective of maintaining a reference angular velocity and one control loop for controlling the load.

3.1. Design of Controller

In this paper, linear quadratic control (LQ) is used for the control design. LQ is a suitable way to control several input signals without adding complexity to the system. The feedback gains of the cross-coupled states are thereby automatically designed to achieve the desired control demands. The LQ technique requires all states to be known or estimated by an observer. The estimation algorithm can also be formed using LQ, which is commonly denoted Kalman filter, forming an LQG system. The proposed system controller for this application is shown in **Figure 4**. The control is based on a state feedback (large arrow) together with a feed forward link from the reference signal. The feed forward link is formed with a non-linear static model of the system calculating the desired displacement settings based on the current system working point (dotted arrows). This configuration represents an open-loop control of the transformer, but does not consider system dynamics or possible model errors. A state feedback is connected in parallel to this in order to achieve the desired closed loop capabilities. The feedback gain L is derived using the LQ technique and applied on the error signal from the calculated working point and the measured states. To compensate for the varying dynamics of the system, feedback gain

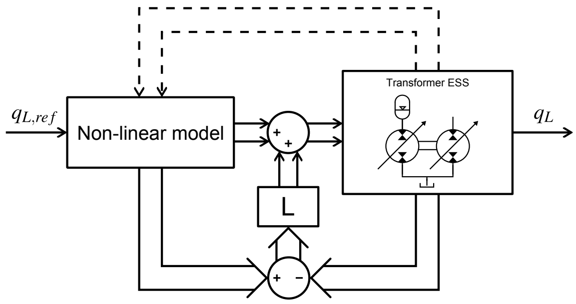


Figure 4: The proposed controller uses a feed forward gain on the reference signal based on the current working point of the system. The state feedback compensates for the dynamics of the system and reduces stationary errors due to model inaccuracies.

must be adjusted in order to obtain similar closed loop behavior at all working points. This is commonly denoted as gain-scheduling and should be based on the knowledge acquired from the linear analysis.

3.2. Extra Degree of Freedom

It is also in place to discuss how to handle the additional degree of freedom the two-machine transformer enables. Given a certain pressure transformation, the machine displacements are fixed to a certain ratio, but allow individual variations within that ratio. One possible strategy is to minimize the losses of the hydraulic machines by choosing to work at higher displacements and a lower shaft speed. Another is to compromise efficiency, to achieve a higher shaft speed and consequently preferable system dynamics. In reality, a mixed strategy might be the best option, where efficiency is prioritized during higher reference flows, when the shaft speed is high enough to achieve sufficient dynamic properties. In the single machine transformer /3/, the system is reduced to a Single Input-Single Output control problem. For a given valve plate position, there is a fix relationship in displacement of the pistons under each kidney.

4. Controller Implementation

In this chapter, the suggested control strategy is used to derive a simple controller for one considered level of complexity. The system model used is shown in **Figure 5** and the governing equations in (1). The model includes a simple friction model of the shaft with

Coulomb friction and viscuous friction. The machine losses are modelled with efficiency look-up tables supplied from the manufacturer. The control units of the displacement machines are modelled with first-order low-pass filters.

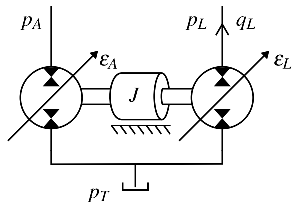


Figure 5: The considered system used to derive the controller implementation. The accumulator dynamics are assumed to be slow and the pressure is consequently considered to be a constant system parameter.

$$J\dot{\omega} + B_v\omega + T_C = \frac{\Delta p_A D_A \varepsilon_A}{2\pi} - \frac{\Delta p_L D_L \varepsilon_L}{2\pi} \pm T_{loss}(\varepsilon_L, \varepsilon_A, \omega, \Delta p_L, \Delta p_A) \tag{1a}$$

$$q_L = \varepsilon_L D_L \omega \pm q_{loss}(\varepsilon_L, \omega, \Delta p_L) \tag{1b}$$

$$\dot{\varepsilon}_L = -\frac{\varepsilon_L}{\tau_L} + \frac{\varepsilon_{Lref}}{\tau_L} \tag{1c}$$

$$\dot{\varepsilon}_A = -\frac{\varepsilon_A}{\tau_A} + \frac{\varepsilon_{Aref}}{\tau_A} \tag{1d}$$

The linearised model of the system around a working point (marked *) is shown in (2). The displacement machines are here considered to be loss-free.

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u} \tag{2a}$$

$$\mathbf{y} = C\mathbf{x} \tag{2b}$$

where

$$A = \begin{bmatrix} -\frac{B_v}{J} - \frac{1}{\tau_L} & \frac{\Delta p_A D_A D_L \varepsilon_A^*}{2\pi J} - \frac{2\Delta p_L D_L^2 \varepsilon_L^*}{2\pi J} - \frac{D_L T_C}{J} & \frac{\Delta p_A D_A D_L \varepsilon_L^*}{2\pi J} & \frac{D_L \varepsilon_L}{\tau_L} \\ 0 & -\frac{1}{\tau_L} & 0 & 0 \\ 0 & 0 & -\frac{1}{\tau_A} & 0 \\ 0 & -\frac{\Delta p_L D_L}{2\pi J} & \frac{\Delta p_A D_A}{2\pi J} & -\frac{B_v}{J} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{D_L\omega}{\tau_L} & 0 \\ \frac{1}{\tau_L} & 0 \\ 0 & \frac{1}{\tau_A} \\ 0 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{x} = \begin{bmatrix} \Delta q_L & \Delta\varepsilon_L & \Delta\varepsilon_A & \Delta\omega \end{bmatrix}^T, \quad \mathbf{u} = \begin{bmatrix} \Delta\varepsilon_{L,ref} & \Delta\varepsilon_{A,ref} \end{bmatrix}^T$$

In this case, all states except the flow are assumed to be measurable. The flow is estimated with a simple observer, including volumetric losses in the same way as described above, according to equation (3):

$$q_{L,est} = \varepsilon_L D_L \omega \pm q_{loss,est} \tag{3}$$

A constant bias to the actual flow is not seen as a problem if the system is implemented in for instance a construction machine, since the operator acts an outer control loop for the actuator motion. It is also noticeable that the feedback is purely proportional, why some control errors cannot be completely compensated. There are, however, possibilities to include additional integrating states in the control implementation to reduce stationary errors. The state feedback is constructed with the *lqr* command in MATLAB and modified online with respect to changes in the accumulator pressure. For simplification, ε_L is in this case chosen to have a fixed reference value, while the reference for ε_A is calcuated within the feed forward link from $q_{L,ref}$.

5. Evaluation

The evaluation of the developed controller has been made using a non-linear simulation model of the system and hardware experiments on a hardware test bed.

5.1. Simulation Model

Simulation tests have been made using the simulation software AMESim /12/ in cosimulation with MATLAB Simulink. The model is shown in **Figure 6** and includes efficiency maps for both hydraulic machines with respect to pressure, speed and displacement. The accumulator model is taken from the standard AMESim library and the load and tank pressures are considered to be ideal.

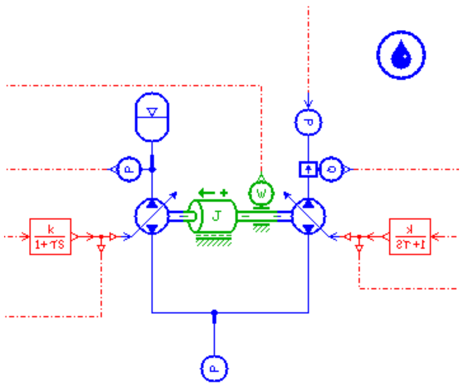


Figure 6: The AMESim model used for controller implementation

5.2. Hardware Model

A hardware test bed has been constructed to further test the controller, see **Figure 7**. The hydraulic transformer is an assembly of two Bosch Rexroth (A4VG) displacement machines with a common mechanical shaft. Each machine is equipped with a swash angle sensor and the rotational speed is measured with a hall transducer from the shaft. The test bed quantities can be found in **Table 1**.

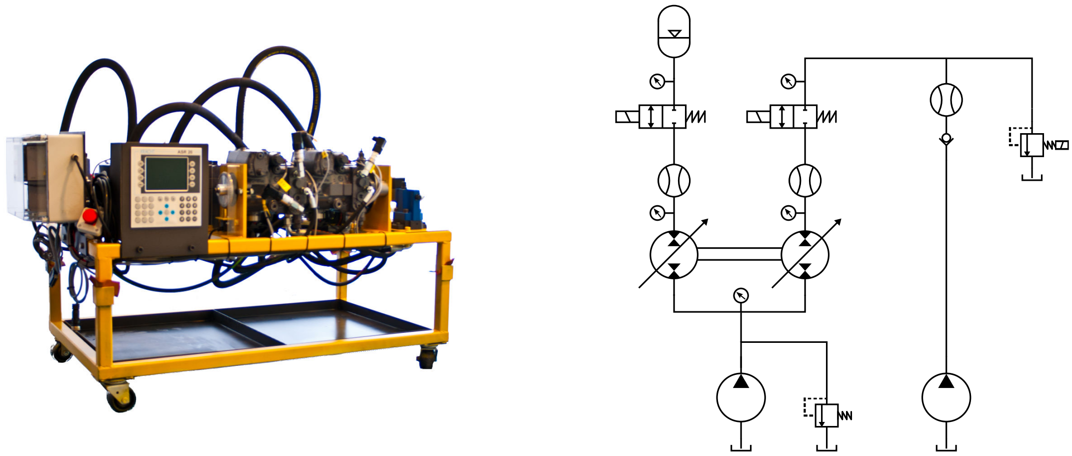


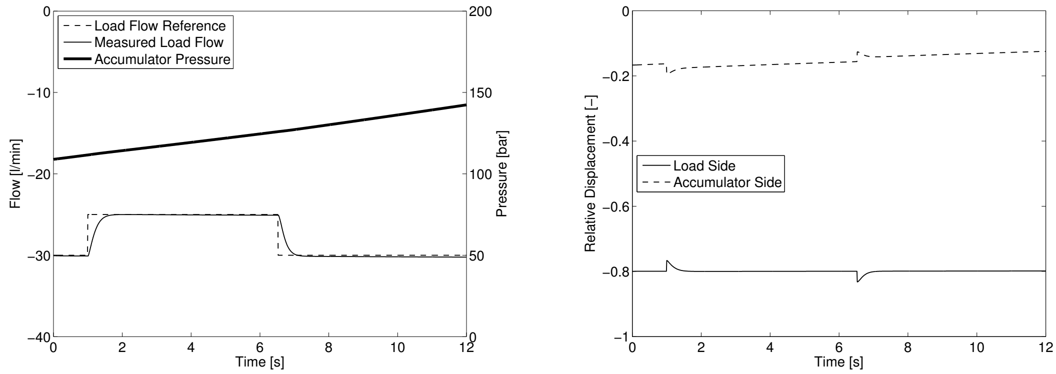
Figure 7: The hardware testbed is supplied with one pressure level for the low pressure side of the transformer and one controllable pressure level simulating the load pressure. The flow meters are used for model validation and analysis and not for control inputs.

Quantity	Description	Value
D_L	Maximum Displacement Load Side	28 cm^3/rev
D_A	Maximum Displacement Accumulator Side	28 cm^3/rev
p_T	Tank Pressure	25 bar
V_0	Accumulator Size	0.01 m^3

Table 1: Test bed properties.

5.3. Results

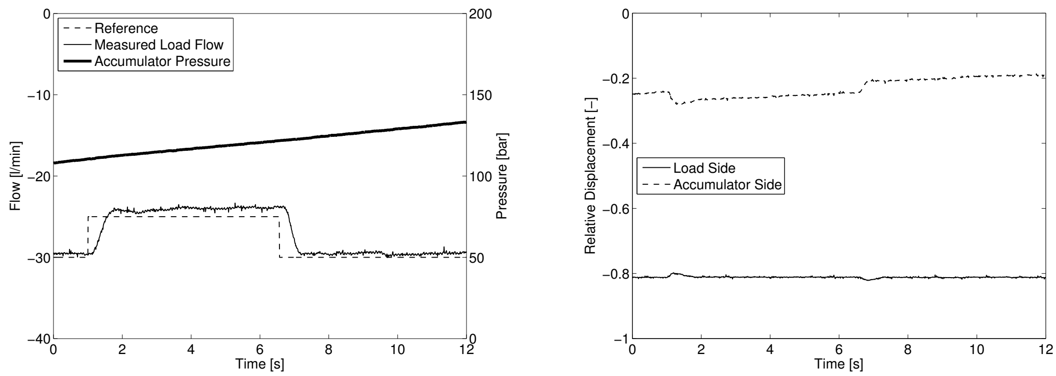
Simulation results for loading the accumulator in the simulation model is shown in **Figure 8a**. **Figure 8b** shows the corresponding relative displacements for the machines.



(a) Flow reference tracking. (b) Machine displacements.

Figure 8: Simulation results.

The state feedback causes both machines to react to the steps in flow reference, which gives a superior performance compared to controlling only one machine. By adjusting the weights in the penalty function when constructing the state feedback gain, this behaviour can be controlled. **Figure 9** shows the same loading case performed in the hardware test bed. The non-linear model in the feed forward link, and consequently the controller performance, is dependent on the accuracy of the efficiency models of the hydraulic machines. In the hardware experiments, these are harder to predict which cause stationary errors in the reference tracking.



(a) Flow reference tracking. (b) Machine displacements.

Figure 9: Results from the hardware experiment.

Another indication of good controller performance is the ability to suppress load disturbances. The feed forward link in the suggested control design compensates for changes in surrounding pressures, but to avoid stationary errors, an additional state with integral action may be added, see /10/. **Figure 10** shows the suppression of external load disturbances with and without an additional integrating state in the controller.

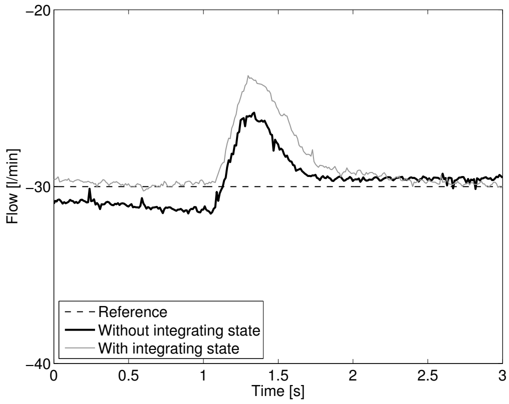


Figure 10: A step of 10% of the load pressure is made after 1 second.

6. Discussion and Conclusion

A control strategy for the transformer-based energy storage system has been proposed, consisting of a non-linear model as feed forward link and a state feedback based on the LQ technique. This combination allows good flow reference tracking and quick response time, given that the transformer is in motion. The start-up process and control at very low shaft speeds is, however, a critical control issue in the proposed concept. The control effort of the mechanically connected parallel hybrid is consequently less, due to the coupling to the engine shaft. One might argue that the acceleration process is too costly and that the transformer should be kept running even when not in use. Drag losses are then also introduced in this concept. One option would be to stop the transformer when the vehicle is in transportation mode and keep it running while operating in working cycles.

A simple controller implementation has been developed according to the suggested control strategy and evaluated in both simulation and hardware experiments. It is shown that acceptable closed loop reference tracking can be achieved with fairly simple models of the system, both in simulation and experiments. One critical point in this process is the friction model of the transformer. When underestimated, the transformer risks stopping completely due to the low inertia and the comparatively slow control dynamics of the machines. If overestimated or insufficiently modelled, the trajectory tracking is instead compromised. The actual friction of the displacement machines is problematic due to its non-linearity, even at higher speeds. The transformer losses should be more closely modelled when applying a more sophisticated controller implementation.

7. Nomenclature

Quantities

p	hydraulic pressure	Pa
q	hydraulic flow	m^3/s
B_v	viscous friction coefficient	Nm/(rev/s)
D	maximum displacement	m^3/rev
J	inertia	kgm^2
T_C	Coulomb friction torque	Nm
ε	relative displacement	-
ω	rotational velocity	rev/s
η_{est}	estimated volumetric efficiency	-
τ	time constant	s

Subscripts

A	accumulator side
L	load side
loss	machine losses
ref	reference

Abbreviations

ESS	Energy Storage System
ICE	Internal Combustion Engine
LQ	Linear Quadratic Control
LQG	Linear Quadratic Gaussian control
MTR	Modulated Transformer

References

/1/ Ming-Chang Shih. *Untersuchung Einer Zylinderansteuerung durch Hydro-Transformator am Konstant Drucknetz*. PhD thesis, Rheinisch-Westfälischen Technischen HochSchule Aachen, Aachen, 1984.

/2/ Rolf Kordak. Hydrostatic Drives with Control of the Secondary Unit. In *The Hydraulic Trainer, Volume 6*. Mannesmann Rexroth, 1996.

/3/ Peter A J Achten, Zhao Fu, and Georges E M Vael. Transforming Future Hydraulics: a New Design of a Hydraulic Transformer. In *The Fifth Scandinavian International Conference on Fluid Power, Linköping, Sweden*, 1997.

/4/ Ronnie Werndin and Jan-Ove Palmberg. Hydraulic Transformers in Low Speed Operation - A Study of Control Strategies. In *The 5th International Symposium of Fluid Power, JFPS'02, Nara, Japan*, 2002.

/5/ Elton Bishop. Digital hydraulic transformer - approaching theoretical perfection in hydraulic drive efficiency. In *The 11th Scandinavian International Conference on Fluid Power, Linköping, Sweden*, 2009.

/6/ Emanuele Guglielmino, Claudio Semini, Helmut Kogler, Rudolf Scheidl, and Darwin G Caldwell. Power Hydraulics - Switched Mode Control of Hydraulic Actuation. In *The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan*, pages 3031–3036. IEEE, 2010. ISBN 9781424466764.

/7/ Kim Heybroek, Jonas Larsson, and Jan Ove Palmberg. The Potential of Energy Recuperation in Valve Controlled Mobile Hydraulic Systems. In *The Eleventh Scandinavian International Conference on Fluid Power, Linköping, Sweden*, 2009.

/8/ Masahiro Egawa and Haruhiko Kawasaki. Study of Electro-hydraulic Energy Saving System (EHESS) for Construction Machinery. In *The Twelfth Scandinavian International Conference on Fluid Power, Tampere, Finland*, 2011.

/9/ Tianliang Lin, Qingfeng Wang, Baozan Hu, and Wen Gong. Research on the Energy Regeneration Systems for Hybrid Hydraulic Excavators. *Automation in Construction*, 19(8):1016–1026, 2010. ISSN 09265805. doi: 10.1016/j.autcon.2010.08.002.

/10/ Jerker Lennevi. *Hydrostatic Transmission Control*. PhD thesis, Linköping University, 1995.

/11/ Sun Wei. *On Studies of Energy Regeneration System for Hydraulic Manipulators*. PhD thesis, Tampere University of Technology, 2004.

/12/ LMS International. *LMS Imagine.Lab AMESim Rev 10 User manual and software*, 2011.