

A Thermal Analysis of Direct Driven Hydraulics

Dr.-Ing. Tatiana Minav

Department of Mechanical Engineering, Aalto University, P.O. Box 14400, 00076, Aalto, Finland, E-mail: tatiana.minav@aalto.fi

Ing. Luca Papini

Power Electronics, Machines and Control Group (PEMC), University of Nottingham, Nottingham, UK, E-mail: luca.papini@nottingham.ac.uk

Professor Dr.-Ing. Matti Pietola

Department of Mechanical Engineering, Aalto University, 00076, Aalto Finland, E-mail: matti.pietola@aalto.fi

Abstract

This paper focuses on thermal analysis of a direct driven hydraulic setup (DDH). DDH combines the benefits of electric with hydraulic technology in compact package with high power density, high performance and good controllability. DDH enables for reduction of parasitic losses for better fuel efficiency and lower operating costs. This one-piece housing design delivers system simplicity and lowers both installation and maintenance costs. Advantages of the presented architecture are the reduced hydraulic tubing and the amount of potential leakage points. The prediction of the thermal behavior and its management represents an open challenge for the system as temperature is a determinant parameter in terms of performance, lifespan and safety. Therefore, the electro-hydraulic model of a DDH involving a variable motor speed, fixed-displacement internal gear pump/motors was developed at system level for thermal analysis. In addition, a generic model was proposed for the electric machine, energy losses dependent on velocity, torque and temperature was validated by measurements under various operative conditions. Results of model investigation predict ricing of temperature during lifting cycle, and flattened during lowering in pimp/motor. Conclusions are drawn concerning the DDH thermal behavior.

KEYWORDS: thermal modelling, direct driven hydraulics, non-road mobile machinery, electro-hydraulic actuator

1. Introduction

The next exhaust limits for engine manufacturers will be implemented in 2019/2020 /1/. This Tier V limit imposes a sharp tightening of exhaust limits, especially in terms of particles. This coming four-year window should be exploited for preparing engines for the upcoming regulations by developing innovative solutions. In order to reach the target environmental requirements, electric and hybrid topologies have seen as suitable solutions. Whereas, a huge potential application area is the Non-road Mobile Machinery (NRMM) industry, which are used in mining, goods manufacturing, forest harvesting, and construction works.

In recent years, an industrial trend can be observed in increased use of compact electro-hydraulic actuators. These actuators are able to deliver powerful, linear movement with valve-controlled or pump-controlled systems. The concept of electrohydraulic actuators have been introduced as zonal hydraulics in NRMM and aircraft applications. For instance in /2/, an electrohydraulic actuator was applied to the power steering of heavy vehicles. In /3, 4/, the new design of electro-hydraulic actuators was developed for aircraft applications, where reliability requirements are very high. Most of the research studies related to electrohydraulic actuators have been conducted to adjust the state of the servo valve /5, 6/, where the set of valves is utilized to balance the flow and to ensure the direction of the electrohydraulic actuator motion. In /7, 8/, the Direct Driven Hydraulics (DDH) unit without conventional directional valves was introduced as an electro-hydraulic actuator. The DDH drive combines the best properties of electric and hydraulic drive technologies in one: Direct control of flow, velocity and position of the actuator; Disconnection of pump units from the internal combustion engine; Possibility of power on demand.

In this research, Direct Driven Hydraulics (DDH) is seen as a tool to convert existing NRMMs to hybrids and/or increase degree of hybridization. In terms of continuous operation, research all around the world is facing the challenge of establishing and maintaining industrial activities in extreme environments. Normally, the heat generated from the equipment operation keeps the fluid warm and enables it to circulate properly. The problems occur at start-up, when everything has cooled down to low temperatures. Equipment failure is unacceptable in remote locations in extreme environments such as the Arctic areas. At the moment, research on the extreme operation of NRMM is limited mostly to the cold-start characteristics of engines /9/ and to the development of new components and hydraulic oils specifically for arctic conditions /10-13/. Heat generation and transfer in oil-hydraulic systems is discussed and researched from an overheating

point of view only /14/ or predicting accurate temperature /15-17/. For instance in /18, 19/, the thermo-dynamical behavior of electro-hydraulic systems were studied in typical working temperatures (above 0 ° C). In /19-22/, a compact drive and its components were investigated from the thermal point of view. New configurations in NRMM with a DDH conversion as hybrid tool are possible without the traditional source of heat and constantly operating engine. Would the DDH unit be self-sufficient from thermal point? Therefore to find answer to this question, this paper investigates directly driven hydraulic setup (DDH) for non-road mobile machinery (NRMM) application from thermal point of view.

The remainder of this paper is organized as follows. The DDH test setup is introduced in Section 2, while Section 3 presents a detail description of the thermal model. The measurement results and their analysis are described in Section 4, thereafter; Section 5 contains discussion and concluding remarks.

2. Test setup

The experimental test setup is illustrated in **Figure 1**. The control of the DDH system is implemented directly with a servo motor drive without conventional hydraulic control valves. Therefore, velocity of the double-acting cylinder is determined by in-coming oil flow from the pump, out-coming flow to the hydraulic motor and angular speed of the electric motor. The electromechanical drive (frequency converter controlled electric motor) is adopted to control the fluid flow, the position of the payload and the direction of the motion. A program for the electric drive is set up to control both the electrical and hydraulic sides of the system, thus allowing good controlled lifting-lowering movement at different speeds and payloads. Test setup consists of two XV-2M internal gear pump/motor by Vivoil with displacement of 14.4 and 22.8 cm³/rev P₂ and P₁, respectively /23/. The size of the pumps (and thus manufacturer) were chosen to match to the unsymmetrical cylinder chambers (MIRO C-10-60/30x400). Unidrive SP1406 drive converts the AC power supply from the line and allows to set the speed of the permanent magnet brushless servo motor Unimotor 115U2C manufactured by Emerson Control Techniques, taking advantage of the information obtained by the feedback device fitted, to ensure the rotor speed is exactly as demanded /24/. Speed and torque of the motor shaft is monitored by Unidrive SP1406 drive software/25/. **Figure 1a** illustrates simplified schematics of test setup with the locations of pressure and height sensors. The pressures of the lines, pump inlet and outlet, are measured by means of Gems 3100R0400S pressure transducers /26/. The actual velocity and height of the cylinder's

piston rod were measured by means of a wire-actuated encoder SIKO SGI (IV58M-0039) /27/.

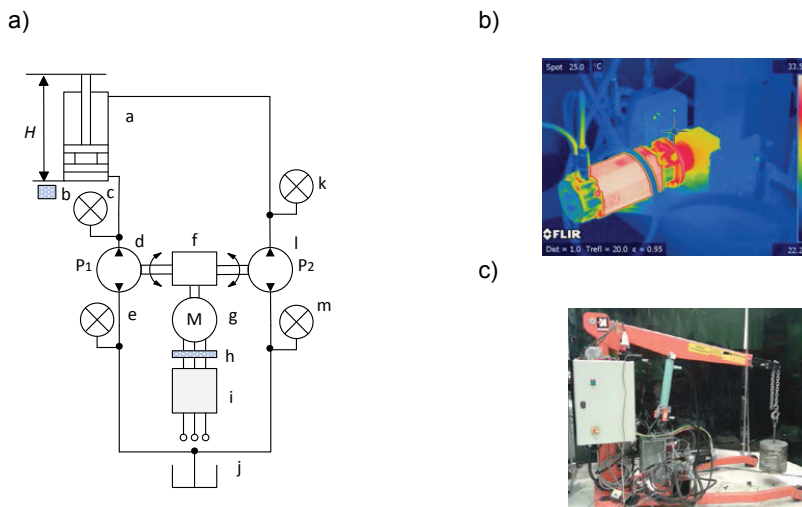


Figure 1: a) schematic of DDH setup, b) thermal image of setup in 10 °C ambient temperature, c) overview of DDH setup

Thermal images across the pump and electrical machine demonstrate of the components different heat loss distribution. Change in fluid temperature (ΔT) across the pump indicates of hydro-mechanical losses within the pump and demonstrates its behavior. Thermal images with larger temperature differential show reduced system efficiency as heat generation results in energy consumption and heat load within the system.

3. Modelling

Modelling of the DDH system is divided to two parts. Thermal modelling of hydraulics is demonstrated in Section 3.1. A thermal generic model is proposed for the electric machine in Section 3.2, where energy losses dependent on velocity, torque and temperature. Thus, simulation results are shown in Section 4. Proposed model was validated by measurements in Section 5.

3.1. Thermal-hydraulic model

Mainly the heat generation of the DDH system appear due to power losses in hydraulic components. Hydraulic oil transfer the heat among hydraulic components. Whereas, exchange between external environment is also happening via convection. According to /28/, direction or circulation of oil is important for the heat transferred among hydraulic components. The thermal model hydraulics. **Figure 2a** depicts the thermal-hydraulic

model, which was built from hydraulic components in SimulationX - commercial multi domain simulation tool.

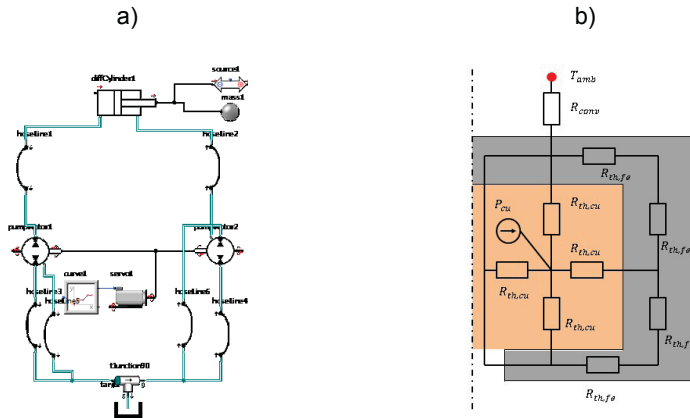


Figure 2: a) Thermal - hydraulic model, b) Lumped parameter model

The DDH system was described as fluidic and solid control volumes, which represents housing of hydraulic components and its solid construction elements. All hydraulic main components are considered in the model. It is assumed that DDH setup has an unlimited heat capacity and remains at ambient temperature equals to 23°C .

3.2. Electric machine thermal model

The electrical drive system consisting of the power electronics linked with electrical machine is designed to achieve a full control of the delivered torque. The characterization of the performances results critical to assess the efficiency of the system. The behavior of the machine is modelled according to analytical equations /29/-/30/ to determine the torque-current characteristic of the device. The different speed-current conditions in which the drive will be operated are expected having an impact in the thermal behavior of the electrical machine, therefore on the overall drive itself. The load capabilities are expected to be fully exploited during the operation of the DDH which reflects in different set point for current injected in the electrical machine at different operative rotor speed. The parameters that characterize the electromagnetic behavior have an impact in the losses that take place in the electrical machine. The current that is injected in the electrical machine will become a source of Joule losses. The rotor speed at which the machine is operated will have a minimum impact on the windage losses (usually considered as $<1\%$ of the total losses /31/), but will have an impact on the iron losses in the stator core due to the time variable magnetic flux provided by the rotor structure. The eddy current losses in the rotor core and permanent magnets are

neglected. The thermal model proposed is designed to evaluate the temperature distribution within the electrical machine structure according to the heat sources that are here considered and dependent on the operative condition of the DDH. The temperature prediction in electrical machine has been a topic highly investigated by many industrial and academic research centers and different techniques has been proposed. Finite Element Methods results as the most accurate technique with the drawbacks of high computational time and time consuming for setting it up; first-second-third order equivalent circuit methods are considered when fast computation is required and are still capable of high accuracy prediction [32]/[33]. Hybrid-mid-complex techniques have been developed to compromise the computational effort and the accuracy of the prediction [34]. The equivalent resistance network [33] has been selected as the modelling tool which better fit the needs of the thermal estimation for the DDH. The proposed model is based on the assumption of symmetrical supply for the electrical machine and the exploitation of the geometrical symmetries of the structure allows reducing the model to a single stator slot. The Fourier equation has been considered discretized for each macro-part in which the computational domain is divided and equivalent thermal resistance and capacitance are defined according to the material thermal properties. The overall result is a linear thermal network which can be solved by means numerical techniques to evaluate the temperature distribution in the nodes. The inputs of the model are the heat losses as previously described: joule losses in the copper winding, heat losses correspondent to the stator iron losses. Boundary conditions have been defined according to the external condition. The cooling media considered in air and natural convection is considered between the stator housing and the environment. The convection coefficient has been defined according to [31]/[32] and the ambient temperature has been changed to replicate the test condition in the controlled thermal chamber. **Figure 2b** illustrates lumped parameter model. The permanent magnet brushless servo-motor 115U2C is characterized by $K_t = 1.6 \text{ Nm/A}$ and $K_v = 9.8 \cdot 10^{-2} \text{ V/rpm}$, with a rated torque of $T_r = 8.1 \text{ Nm}$ with an operative maximum speed of $\omega_m = 3000 \text{ rpm}$. The control system is designed to fulfill the dynamics requirements of the DDH. The current injected is controlled up to $I_{MAX} = 23.5 \text{ A}$. Steady state and transitory operative conditions are considered to validate the thermal model of the machine. The rated current considered defines the value of the heat source in the part of the lumped parameters that models the copper region. The variation of the resistivity with respect the temperature is taken into account according to (1)

$$\rho(T) = \rho_{20^\circ\text{C}}(1 + \alpha_{cu} [T - 20]), \quad [\text{S/m}] \quad (1)$$

where $\rho_{20^\circ C}$ is the resistivity of the copper at $T = 20^\circ C$, α_{cu} is the thermal coefficient of the copper and T is the operative temperature of the material. The joule losses are defined by means (2)

$$P_{cu} = \kappa_{end} N_{ph} N_{turn} \frac{\rho(T)L}{s} I^2, [W] \quad (2)$$

where κ_{end} is the end region correction factor, N_{ph} is the number of phases, N_{turn} is the number of turn/phase, L is the axial length of the machine, s the cross section of the conductors. The iron losses are estimated according to the Steinmetz equation (3)

$$P_{fe} = \kappa_h f^\alpha B^\beta + \kappa_e (f B)^2, [W/kg] \quad (3)$$

where f is the frequency of the magnetic flux density, B is the peak of the magnetic flux density and α, β, κ_h and κ_e are constant coefficient listed in Table 1. The thermal resistances are defined as (4) and connect the macro-sections in which the computational domain is divided.

Parameter	Value
κ_h	0.039
κ_e	0
α	1
β	1.6886

Table 1: Iron Losses coefficients

$$R_{th} = \frac{C_t s}{L}, \quad (4)$$

$$R_{conv} = h s L, \quad (5)$$

where C_t is the conduction coefficient of the material, h is the convection coefficient, s is the surface of heat exchange and L is the axial length /35/. The thermal convective equivalent resistance between the electrical machine and the environment is defined as (5) where the definition of the thermal convection coefficient can be found in /31/. The number of nodes has been chose as a compromise between the accuracy of the prediction and the computational effort required. The thermal capacity of the iron and copper region has been modelled to account for the thermal transitory behavior of the machine.

4. Simulations Results

The thermal model has been tested in ambient operative conditions. The operative behavior of the DDH is considered to be oscillatory. The rotational speed of the electrical machine is controlled in order to achieve a periodic change in pressure required as an output. The amplitude of the current supplied to the machine is defined by means the

speed loop, featuring peaks when change in directions occurs while only small quantities are required when the speed is kept constant. The torque generated results directly proportional with respect to the q-axis current which is approximated with its first harmonic with respect to the period of the hydraulic oscillation considered and expressed in (6). The joule losses are generated by means of the square of the current resulting in I_{heat}

$$I_q(t) = I_M \cos(\Omega_h t + \theta_h) \Rightarrow I_q^2(t) = I_M^2 \cos^2(\Omega_h t + \theta_h) \Rightarrow I_{heat} = \frac{I_M^2}{2}, \quad (6)$$

where I_M is the maximum rms value achieved by the current, Ω_h is the angular speed of the hydraulic oscillation and θ_h its phase angle. The constant equivalent rms current is supplied and the thermal model predicts a transitory 1 °C/cycle increase in the housing and 4 °C/cycle in the hot spot of the winding structure. Results of electric machine thermal modeling are shown in **Figure 3**. The transitory rise of the temperature in the surface where the heat is exchanged, the housing of the electrical machine, is presented in **Figure 3a**. In **Figure 3b**, the temperature in the winding structure, the hot spot of the electrical machine, is reported and the maximum temperature achieved in the motor housing is highlighted with the dashed line. The model developed is capable of accounting also for the transitory heat transmission between the region where the heat sources are located and the surface dedicated to the heat exchange.

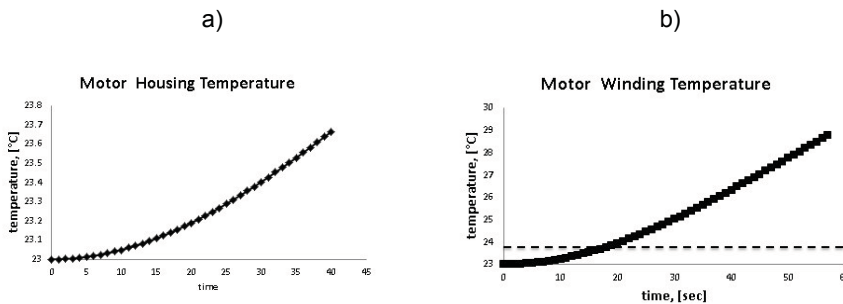


Figure 3: Result of electric machine thermal model: a) Motor housing temperature, b) Motor winding temperature.

Figure 4 shows simulated oil temperature at different locations: pump/motors and tank. As input signal measured data from **Figure 5** was used. Simulation results predict ricing of temperature during lifting cycle, and flattened during lowering in pump/motor.

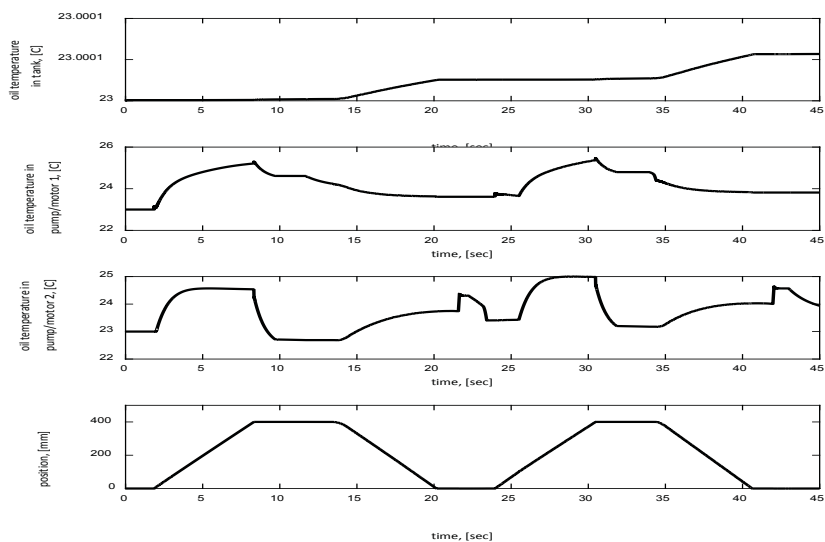


Figure 4: Results of thermal-hydraulic model: position, pump/motors and tank oil temperatures

5. Experimental investigation

The proposed models of DDH is validated by measurements in this Section. The experimental tests are performed in a temperature controlled environment. Essential parameters like pressure, torque, speed, cylinder position and velocity, electric motor voltage, current and ambient temperature are either directly obtained from the setup with sensors or calculated. For experiments a DDH setup was installed according to **Figure 1a**. **Figure 1a** shows the experimental setup with the locations of pressure, height, temperature, current and voltage sensors.

The DDH experimental setup was tested with a payloads of 140 kg at different speeds. The tare weight of the moving boom system is 9.5 kg. **Figure 5** depicts the measurement results for the chosen maximum payload. The payload was lifted to a height of 0.4 m at an average velocity of 0.2 m/s and then lowered to the ground with the same speed. The rotation speed of the PMSM, which corresponds to the pump/motor speed, was 500 rpm. According to **Figure 5**, the torque needed for lifting the payload is equal to 16 Nm, acting pressure reach up to 100 bar. Pressure peak during lifting phase in the system corresponds to unequal pump displacement to cylinder area.

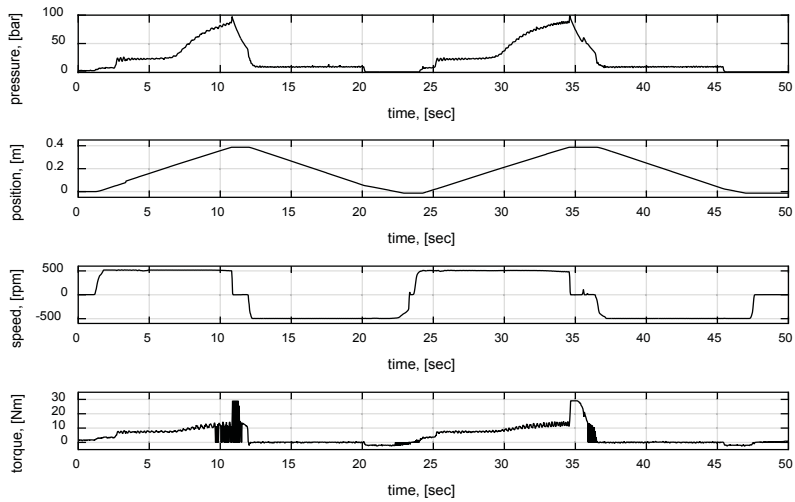


Figure 5: Results of experimental investigation: pressure, height, speed, flowrate and estimated torque.

Figure 6 illustrates temperature changes during lifting lowering cycle.

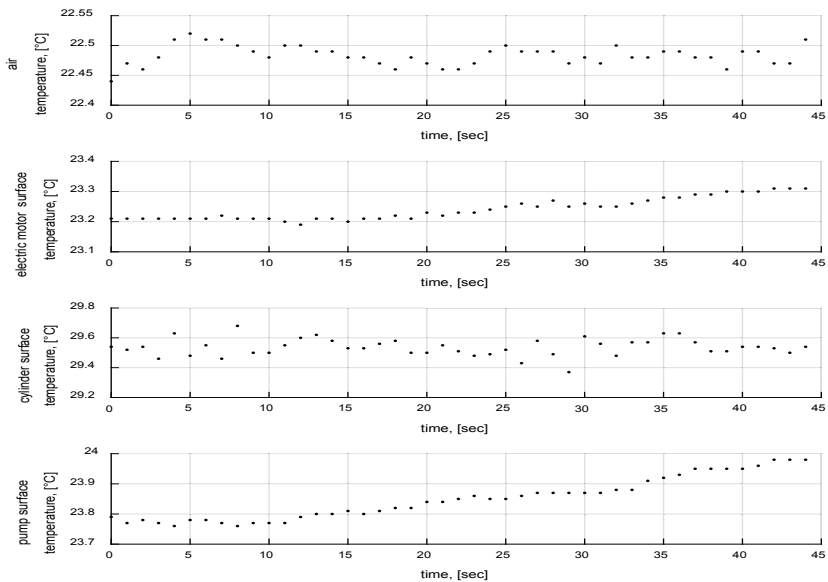


Figure 6: Temperature results of experimental investigation during lifting-lowering cycle.

The comparison of the simulation results with measurements for lifting/lowering cycle with a payload 149.5 kg showed that surface temperature is higher than simulated oil temperature. Influence of pressure peaks in DDH system can be observed in rising temperature in simulation results. Finally, according to simulation during lifting-lowering cycle, the electric motor is the warmest component.

6. Conclusion

There is a rising trend for compact electro-hydraulic actuators in industry. In this study the direct driven hydraulic test setup without control valves was described and investigated from thermal point of view. The comparison between the simulation results and the experimental test data validate the modelling developed for both the electrical machine and the hydraulic system. The experimental tests confirmed rising of temperature during lifting cycle, and flattened during lowering.

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8. References

- /1/ Tier 4 Emission Standards for Nonroad Diesel Engines, online, <https://www.dieselnet.com/standards/us/nonroad.php#tier4>
- /2/ Daher, N., Ivantysynova, M., Electro-hydraulic energy-saving power steering systems of the future. 2012. Proceedings of the 7th FPNI PhD Symposium on Fluid Power, June 27-30, 2012, Reggio Emilia, Italy.
- /3/ Youzhe Ji, Song Peng, Li Geng, Zhanlin Wang, Lihua Qiu, Pressure Loop Control of Pump and Valve Combined EHA Based on FFIM. 2009. The Ninth International Conference on Electronic Measurement & Instruments, 2009.
- /4/ Qian Zhang, Bingqiang Li, Feedback Linearization PID Control for Electro-hydrostatic Actuators, 2011.
- /5/ Liang, B., Li, Y., Zhang, Z., Research on Simulation of Aircraft Electro-Hydrostatic Actuator Anti-Skid Braking System. 2011. Third International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), 6-7 Jan. 2011, pp. 78 – 82
- /6/ Altare, G., Vacca, A., Richter, C., A Novel Pump Design for an Efficient and Compact Electro-Hydraulic Actuator, IEEE Aerospace Conference, 2014 IEEE, 2014, pp. 1-12.
- /7/ Minav, T.A., Bonato, C., Sainio, P., Pietola, M., Direct driven hydraulic drive, at IFK, March 2014, Aachen, Germany.

- /8/ Minav, T.A., Bonato, C., Sainio, P., Pietola, M., Efficiency of Direct Driven Hydraulic Drive for Non-road Mobile Working Machines, at ICEM, September 2014, Berlin, Germany.
- /9/ Hydraulic_Fluids, http://www.statoil-ellas.lv/files/Hydraulic_Fluids.pdf
- /10/ Arctic Low Pour Hydraulic Oil, <http://www.phillips66lubricants.com/documents/>
- /11/ Qinghui Zhou, et.al, Development of Control Strategy for SI Engine Cold Start, IEEE International Conference on Information and Automation June 20 - 23, Harbin, China
- /12/ Waleed Nessim, Fujun Zhang, Powertrain Warm-up Improvement using Thermal Management Systems, International Journal of Scientific & Technology Research Volume 1, Issue 4, MAY 2012
- /13/ Kauranen P., et.al. Temperature optimisation of a diesel engine using exhaust gas heat recovery and thermal energy storage, http://www.vtt.fi/inf/julkaisut/muut/2010/PCMAkku_ATE2009_Submitted.pdf
- /14/ Busquets E., Ivantysynova M., Temperature Prediction of Displacement controlled multi-actuator machines, Int. J. of Fluid Power, Jan., 2014;
- /15/ Busquets E., An investigation of the cooling power requirements for displacement-controlled multi-actuator machines, 2013
- /16/ Michel S., et.al. Energy-efficiency and thermo energetic behavior of electrohydraulic compact drives, 9th IFK conf. 2014
- /17/ Minav,T., P. Sainio, M. Pietola, Efficiency of Direct driven hydraulic setup in arctic conditions, SICFP 2015, May 2015, Tampere, Finland.
- /18/ Soudunsaari R.,Hydrauliöljy ja Hydraulipumppu arktissa olosuhteissa , Espoo : VTT, 1985
- /19/ Rovellini, et.al. Induction motors for use in arctic environments, PCIC Europe 2010 Conf. proceedings.
- /20/ Li Y., et.al. Thermal-hydraulic modeling and simulation of high power hydro-motor, 2008, Asia simulation conference proceedings.
- /21/ Tomioka K., et.al., A Method predicting temperature rise of oil-hydraulic system considering heat balance between oil-passage and housing, Int. Conference on Integrated Modelling and analysis in applied control and automation, 2012
- /22/ Tomioka ,K.,et.al., Precise and Practical 1D Analysis Method of Temperature in an oil-hydraulic cylinder chamber considering 3D internal flow, Transaction of the japan fluid power system society, Vol.43, N2,2012
- /23/ Vivoil motor, Data Sheet: reversible motor - series XV, [Online]. Available: http://www.vivoil.com/files/xm_en/xm201.pdf, visited on September 8, 2013
- /24/ Emerson Control Techniques Unimotor 115U 2C, http://www.emersonindustrial.com/en/en/documentcenter/ControlTechniques/Brochures/unimotor_fm_product_data.pdf, visited on September, 2013.

- /25/ Emerson Control Techniques Unidrive SP1406 drive, <http://www.emersonindustrial.com>, visited on September 8, 2013.
- /26/ Gemssensors 3100R0400S pressure transducers, <http://www.gemssensors.com/Products/Pressure/Pressure-Tranducers> , visited on September, 2013.
- /27/ SIKO SGI (IV58M-0039), <http://www.siko-global.com/en-de> , visited on October, 2013.
- /28/ Kai Li, Zhong Lv, Kun Lu, Ping Yu, Thermal-hydraulic modeling and simulation of the hydraulic su=system based on the electro-hydraulic actuator, *procedia Engineering* 80 (2014) 272-281
- /29/ Bolognesi, P., A mid-complexity analysis of long-drum-type electric machines suitable for circuital modeling, *ICEM 2008*, pp.1-5, 6-9 Sept. 2008 doi: 10.1109/ICELMACH.2008.4799879
- /30/ Rodríguez, A.L.; Gómez, D.J.; Villar, I.; López-de-Heredia, A.; Etxeberria-Otadui, I., Improved analytical multiphysical modeling of a surface PMSM, 2014 International Conference on Electrical Machines (ICEM), pp.1224-1230, 2-5 Sept. 2014, doi: 10.1109/ICELMACH.2014.6960338
- /31/ Howey, D.A.; Childs, P.R.N.; Holmes, A.S., Air-Gap Convection in Rotating Electrical Machines, *IEEE Transactions on Industrial Electronics*, vol.59, no.3, pp.1367-1375, March 2012, doi: 10.1109/TIE.2010.2100337
- /32/ Zhe Huang; Marquez-Fernandez, F.J.; Loayza, Y.; Reinap, A.; Alakula, M., Dynamic thermal modeling and application of electrical machine in hybrid drives, 2014 International Conference on Electrical Machines (ICEM), pp.2158-2164, 2-5 Sept. 2014, doi: 10.1109/ICELMACH.2014.6960483
- /33/ Bracikowski, N.; Hecquet, M.; Brochet, P.; Shirinskii, S.V., Multiphysics Modeling of a Permanent Magnet Synchronous Machine by Using Lumped Models, *IEEE Transactions on Industrial Electronics*, vol.59, no.6, pp.2426-2437, June 2012, doi: 10.1109/TIE.2011.2169640
- /34/ Papini, L.; Gerada, C., Thermal-electromagnetic analysis of solid rotor induction machine, 7th IET International Conference on in Power Electronics, Machines and Drives (PEMD 2014), April 2014, doi: 10.1049/cp.2014.0462
- /35/ Boglietti, A.; Carpaneto, E.; Cossale, M.; Lucco Borlera, A., Stator thermal model for short-time thermal transients, 2014 International Conference on in Electrical Machines (ICEM), 2-5 Sept. 2014, doi: 10.1109/ICELMACH.2014.6960367

9. Nomenclature

- B peak of the magnetic flux density
- C_t conduction coefficient of the material
- f frequency of the magnetic flux density

I_{MAX}	maximum current	A
K_t	torque constant	Nm/A
K_v	voltage constant	V/rpm
κ_{end}	end region correction factor	
L	axial length of the electric machine	m
N_{turn}	number of turn/phase	
N_{ph}	number of phases	
h	convection coefficient	
P_{cu}	joule losses	
P_{fe}	iron losses	
T_r	rated torque	Nm
s	cross section of the conductors	
α_{cu}	thermal coefficient of the copper	
$\rho_{20^\circ C}$	resistivity of the copper at $T = 20^\circ C$	
θ_h	phase angle	
Ω_h	angular speed	Rad/sec
ω_m	maximum speed	rpm