Individual Electro-Hydraulic Drives for Off-Road Vehicles

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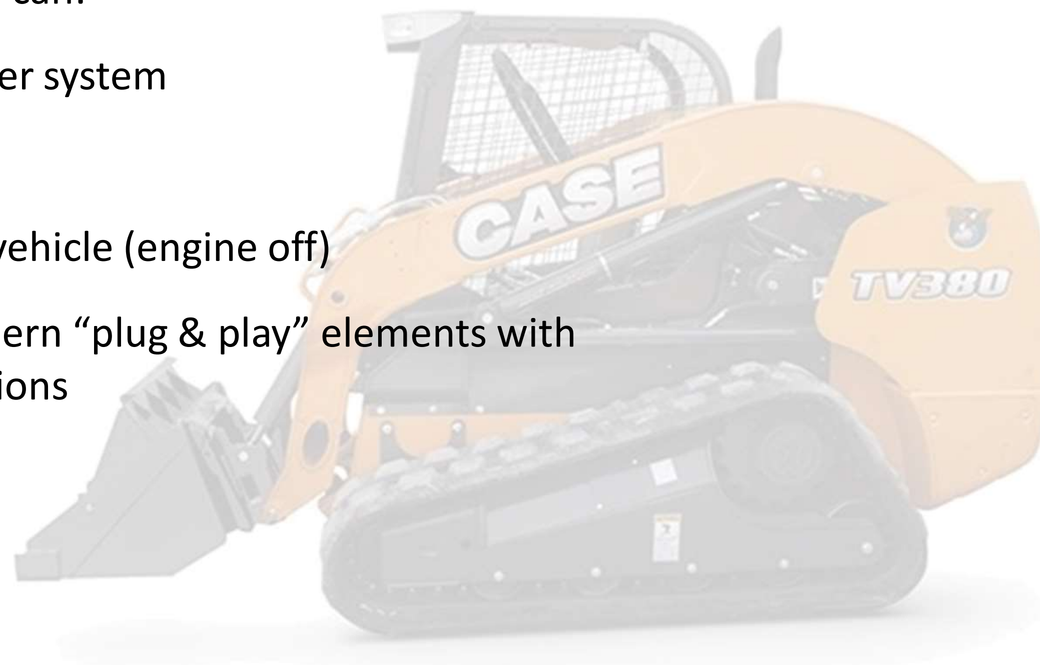
Proposed Objectives

To develop and demonstrate an electro-hydraulic technology that, with respect to current state-off art solutions for off-road vehicles, can:

- ✓ Lower power consumption of the fluid power system
- ✓ Reduce noise and vibrations
- ✓ Allow for "zero emission" operation of the vehicle (engine off)
- ✓ Enable "smart actuators", operating as modern "plug & play" elements with integrated control and self-diagnostic functions



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A Bosch Company

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Electrification trend (off-road examples)

AGCO Fendt e100 Vario

CAT® 988K XE

John Deere 944K

Kramer 5055e

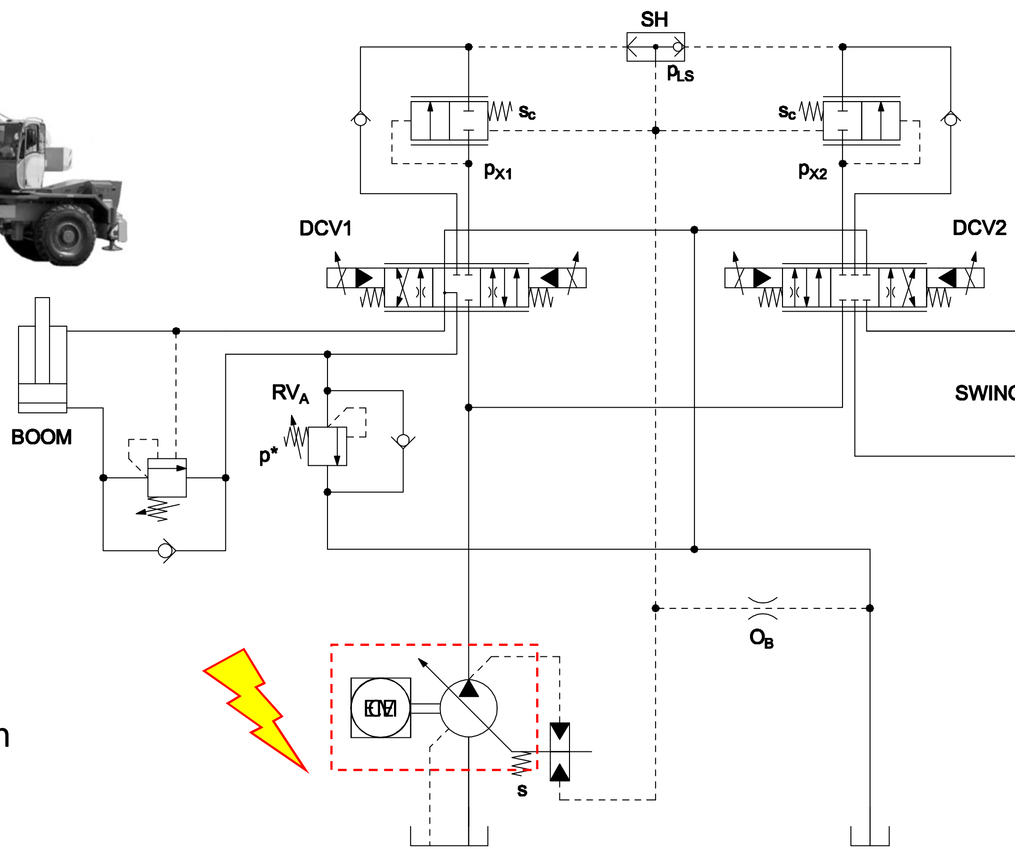
autonomous Volvo HX1

JCB 19C-1 E-TEC

Mitzubishi FBC15N

Hydraulic circuits for electrified machines

Classical centralized architecture

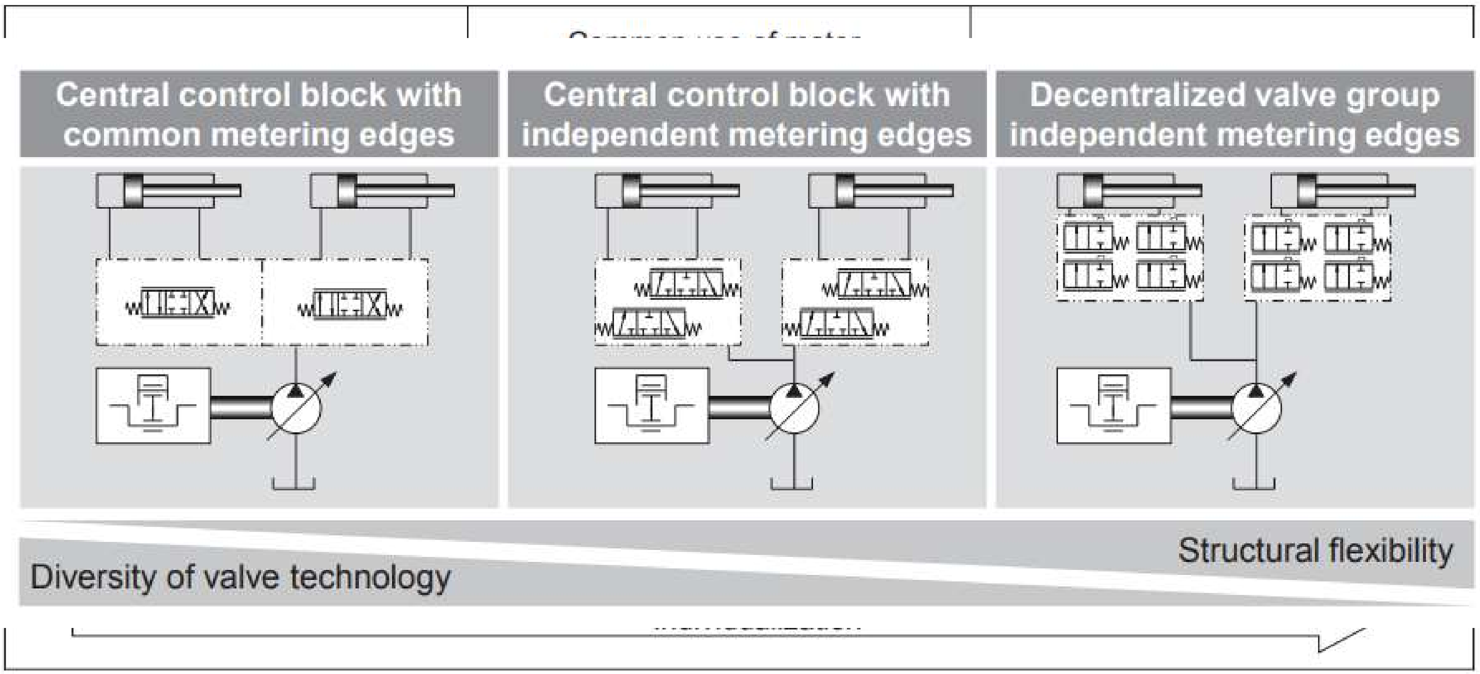


Pros
- ✓ System functionality
- ✓ Cost effective

Cons
- ✓ Fluid throttling
- ✓ Load interference
- ✓ No energy recuperation

Hydraulic circuits for electrified machines

Individualization trend: metering control



Weber J., 2016, *Novel System Architectures by Individual Drives*, 10th Int. Fluid Power Conference, 8-10 March 2016, Germany

Andrea Vacca

Hydraulic circuits for electrified machines

Electro-hydraulic hybrid circuit for the implements of an off-road vehicle

U.S. DEPARTMENT OF ENERGY

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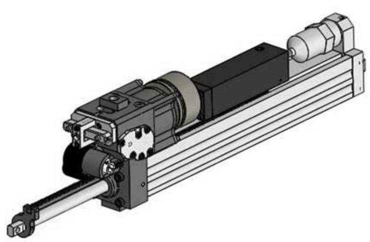
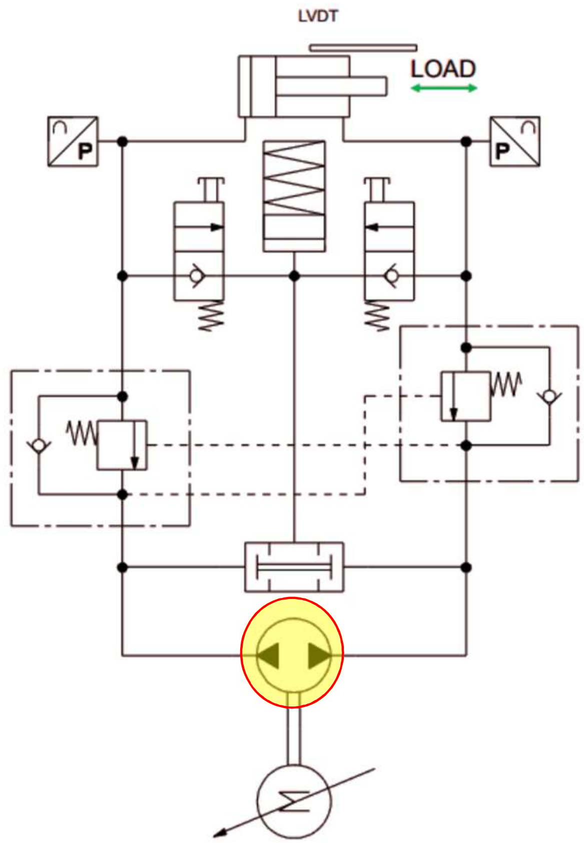
Main features

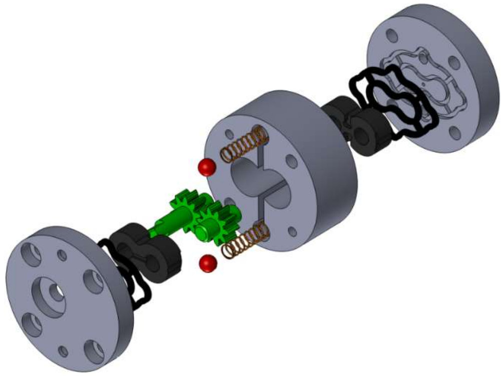
- ✓ Self contained individual drives
- ✓ No fluid throttling
- ✓ Energy recuperation
- ✓ Reduced ICE size
- ✓ Enables smart actuators, operating as modern “plug & play” elements
- ✓ Zero emission modes

Purdue's electro-hydraulic actuator

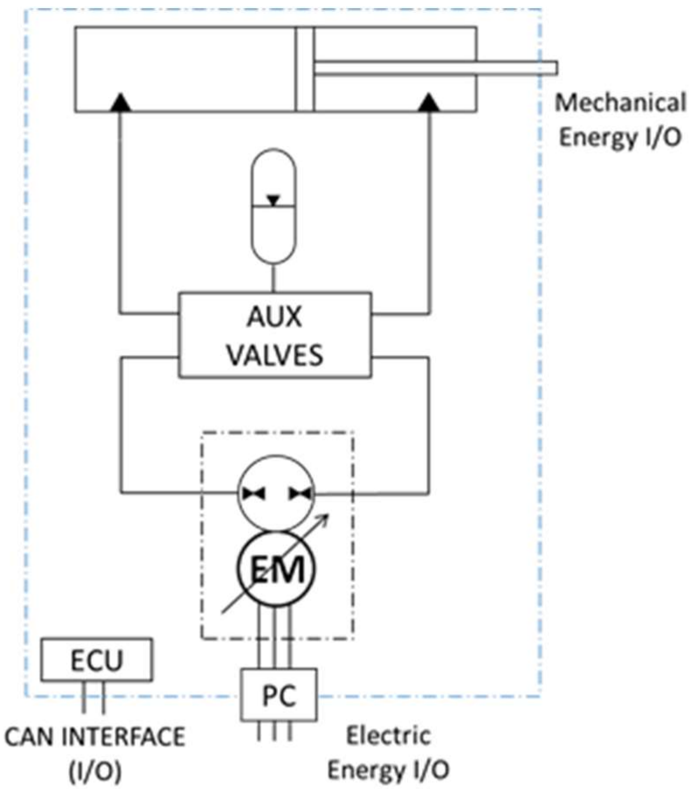




High efficient EHA system layout



Purdue's electro-hydraulic actuator

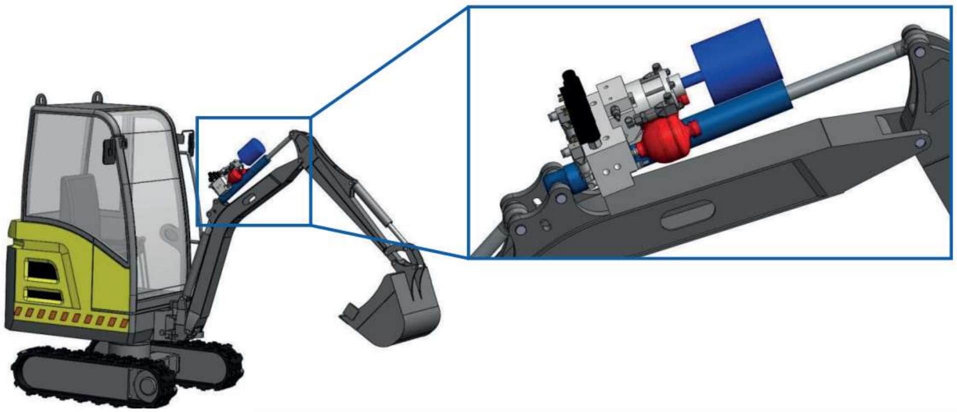


	Efficiency	Dynamics	Costs
AC motor + fixed pump	☹ ☹	☺ ☺ ☺	☺ ☺ ☺
AC motor + variable pump	☺	☺ ☺	☺ ☺
VFD + AC motor + fixed pump	☺ ☺	☹	☺
VFD + AC motor + variable pump	☺ ☺ ☺	☺ ☺	☹

Mattos W., 2016, *4EE – High Performance Energy Efficiency for Hydraulic Machine Drive*, 9th FPNI PhD Symposium on Fluid Power, Oct 26-26, 2016, Florianopolis, Brazil

Electro-hydraulic pump/motor

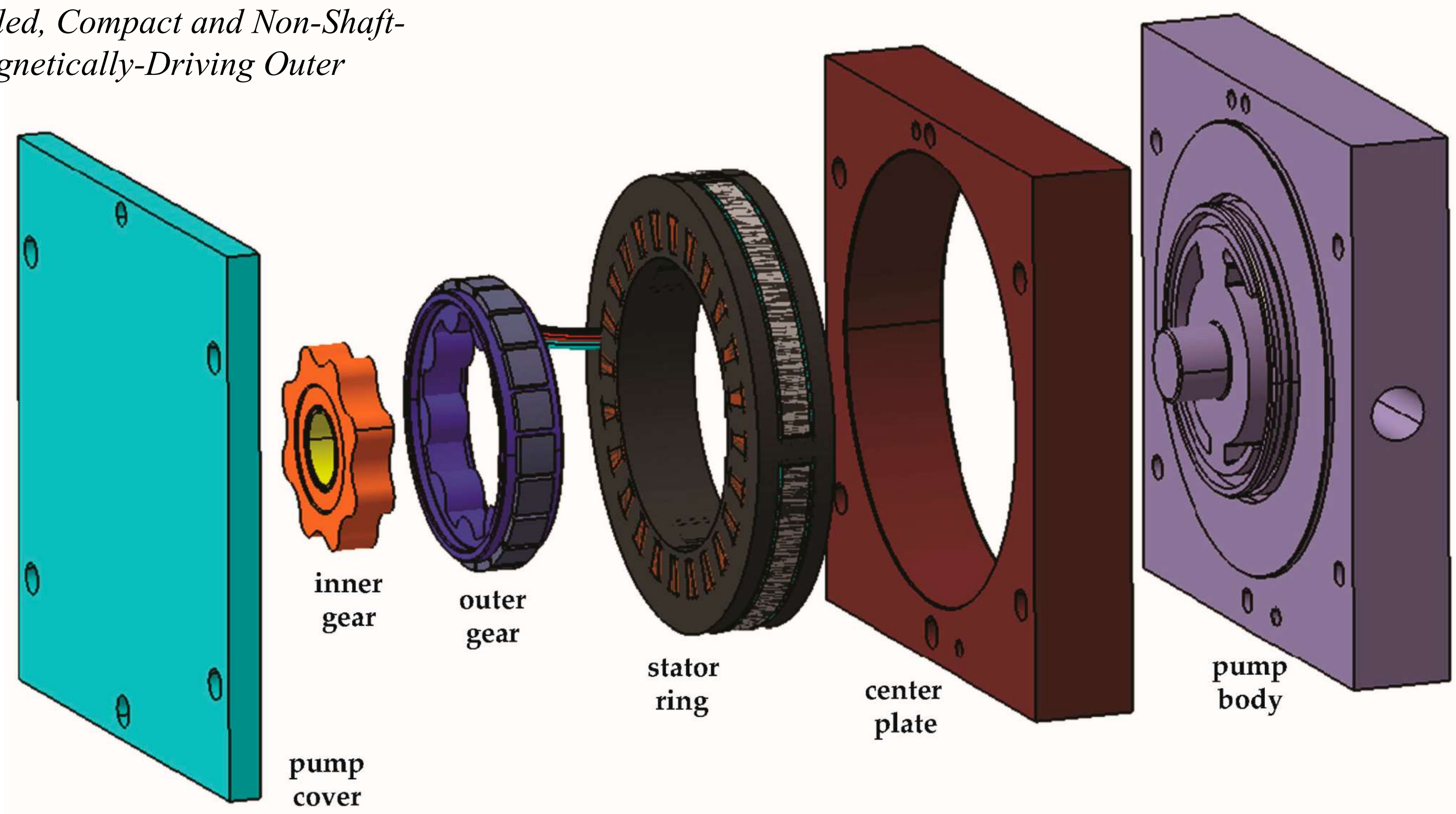
Implementations



Electro-hydraulic pump/motor

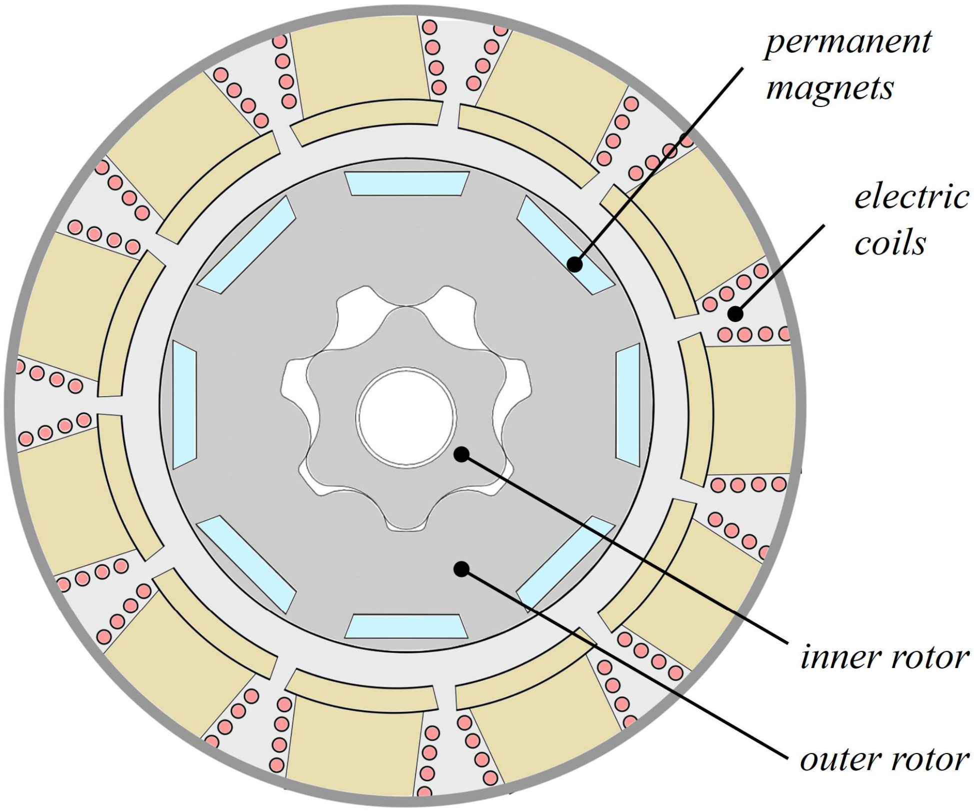
Electric machine and hydraulic machine - design integration

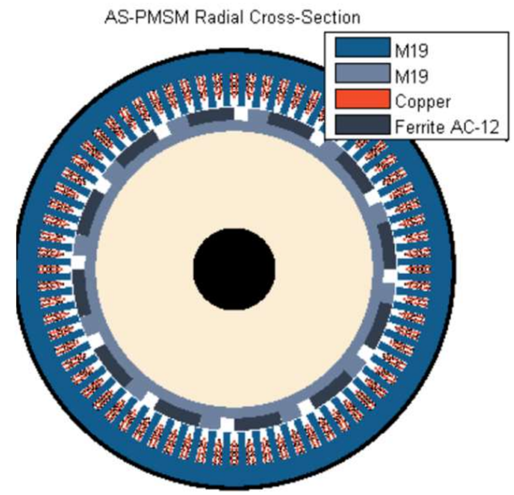
Gamez-Montero P.J. et al., 2017, *GeroMAG: In-House Prototype of an Innovative Sealed, Compact and Non-Shaft-Driven Gerotor Pump with Magnetically-Driving Outer Rotor*. Energies 2017, 10, 435



Electro-hydraulic pump/motor

Integration advantages





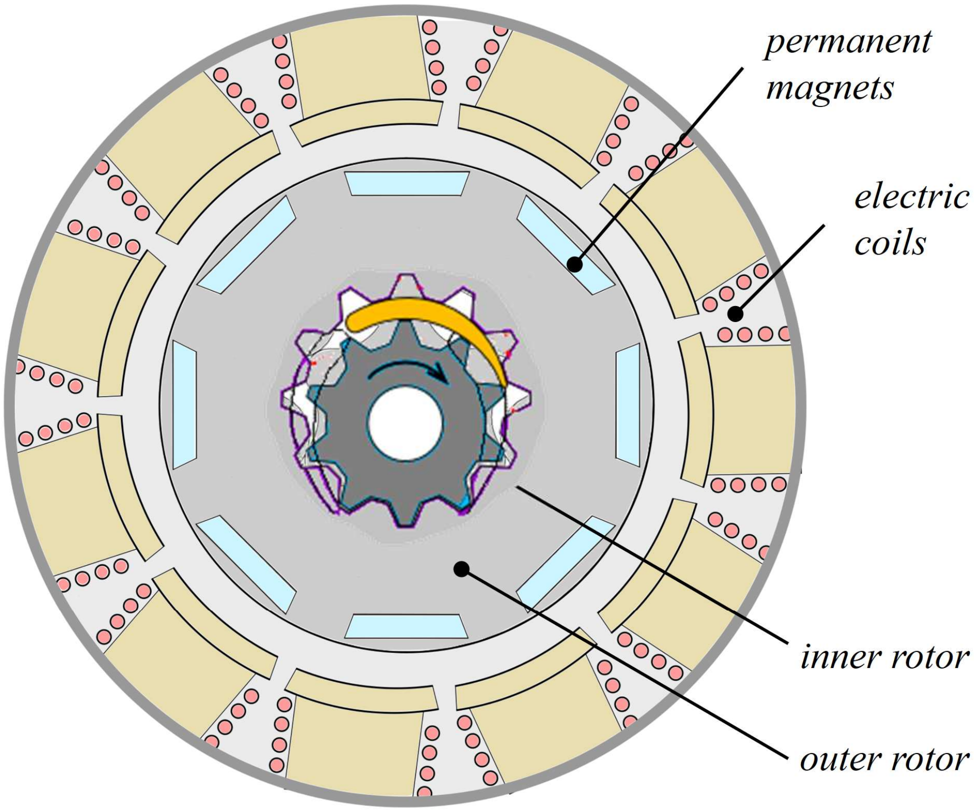
Harianto C., Sudhoff S.D., 2013, *A Rotationally Asymmetric Machine with Improved Torque Density*, IEEE Transactions on Energy Conversion, vol. 28, no. 1, pg(s) 62-75, March 2013

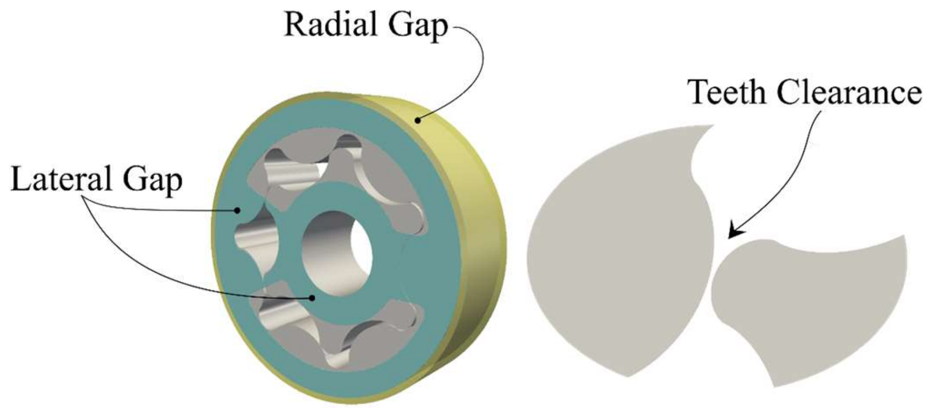
Integration advantages

- ✓ Power to weight ratio
- ✓ Cooling advantage
- ✓ Four-quadrant operation

Electro-hydraulic pump/motor

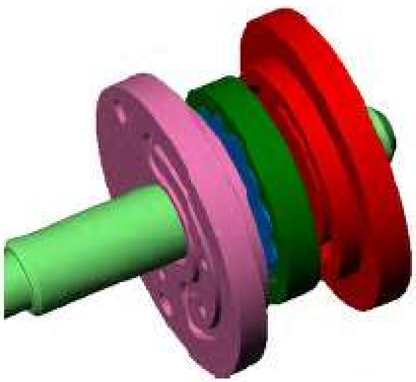
Internal gear machines – high pressure solutions

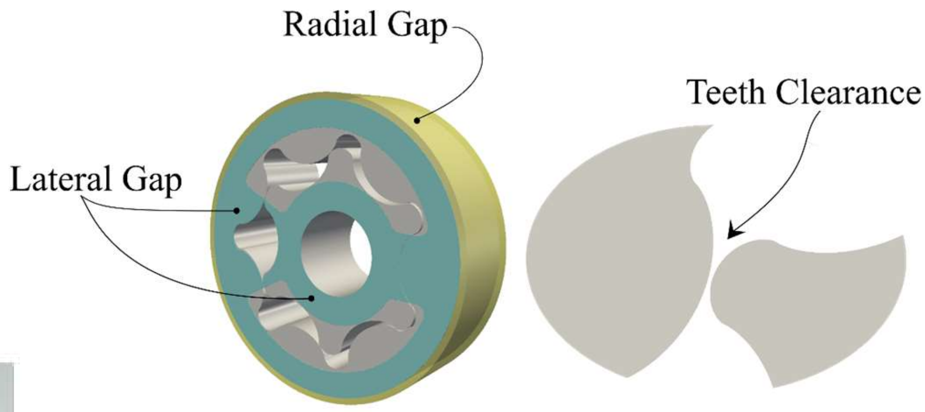




Electro-hydraulic pump/motor

Internal gear machines – gap compensation

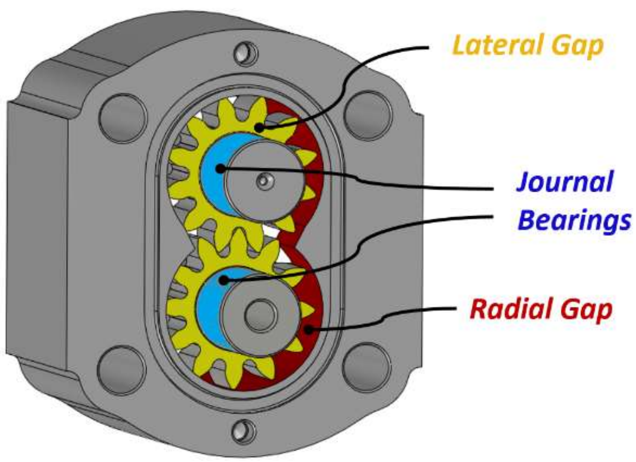


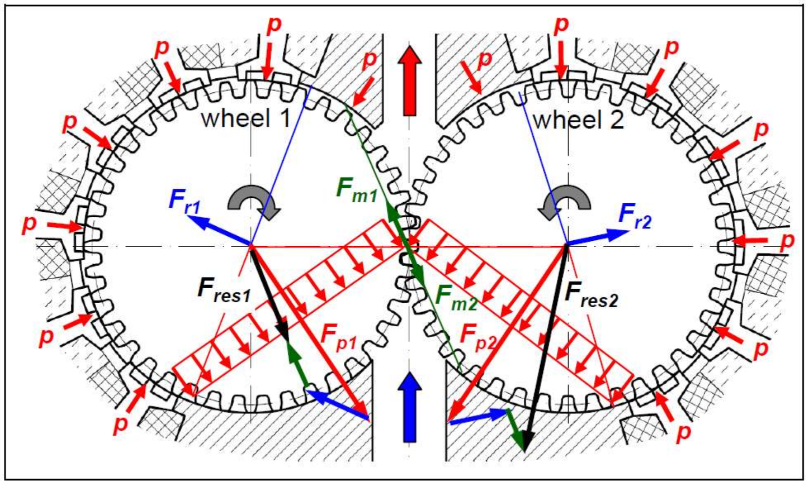


Manco S., Nervegna N., Rundo M., Margaria M., 2002, *Miniature gerotor pump prototype for automotive applications*, International Fluid Power Conference (IFK), Aachen, Germany, March 2002

Electro-hydraulic pump/motor

External gear machines



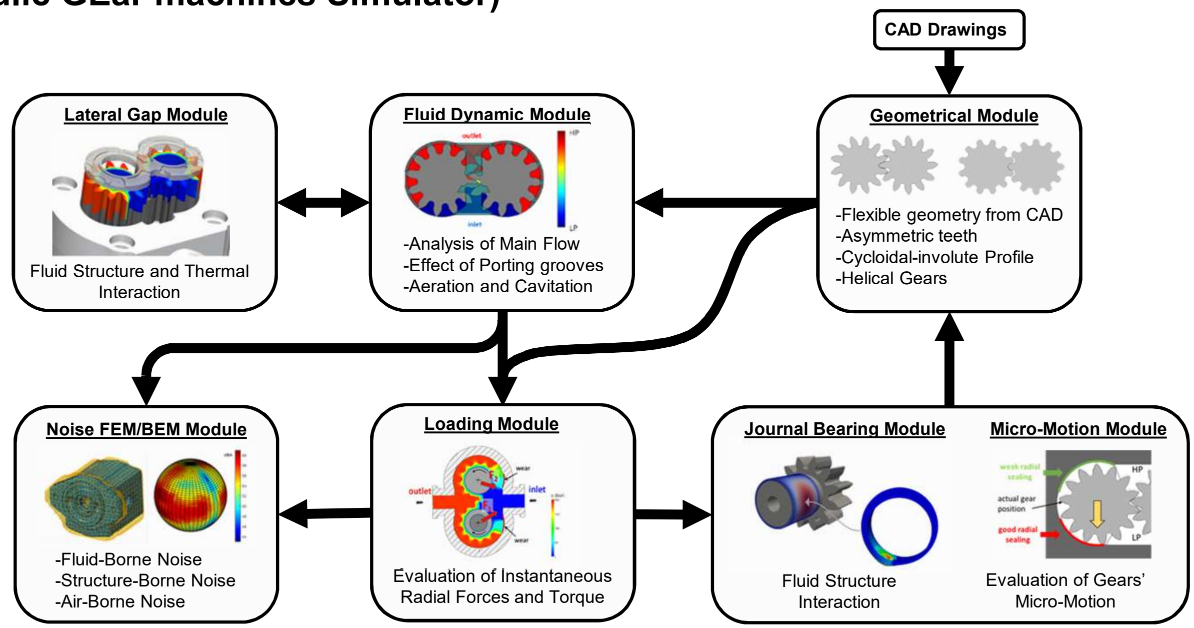


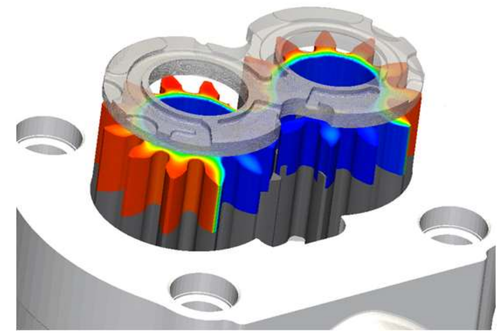
Wustmann W., Helduser S., 2007, *Fully Integrated Electric-Hydrostatic Drive Based on a Gear Pump and a Switched Reluctance Motor*, SICFP'07, May 21-23, 2007, Tampere, Finland

Modeling approach

Modeling

HYGESim (HYdraulic GEar machines Simulator)





Modeling approach

Modeling

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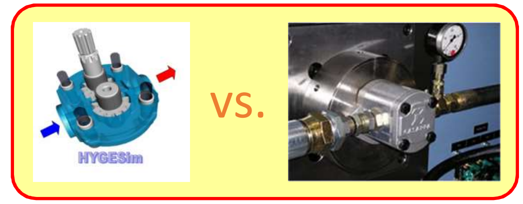
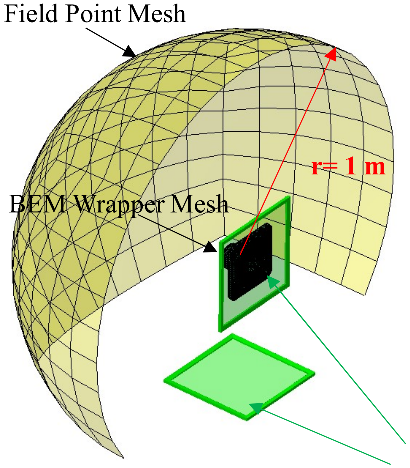
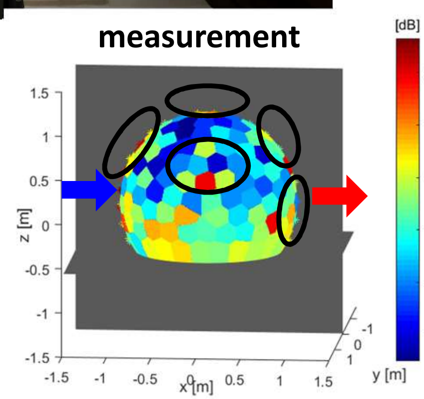
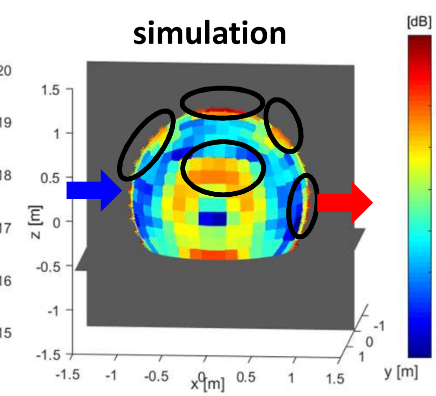


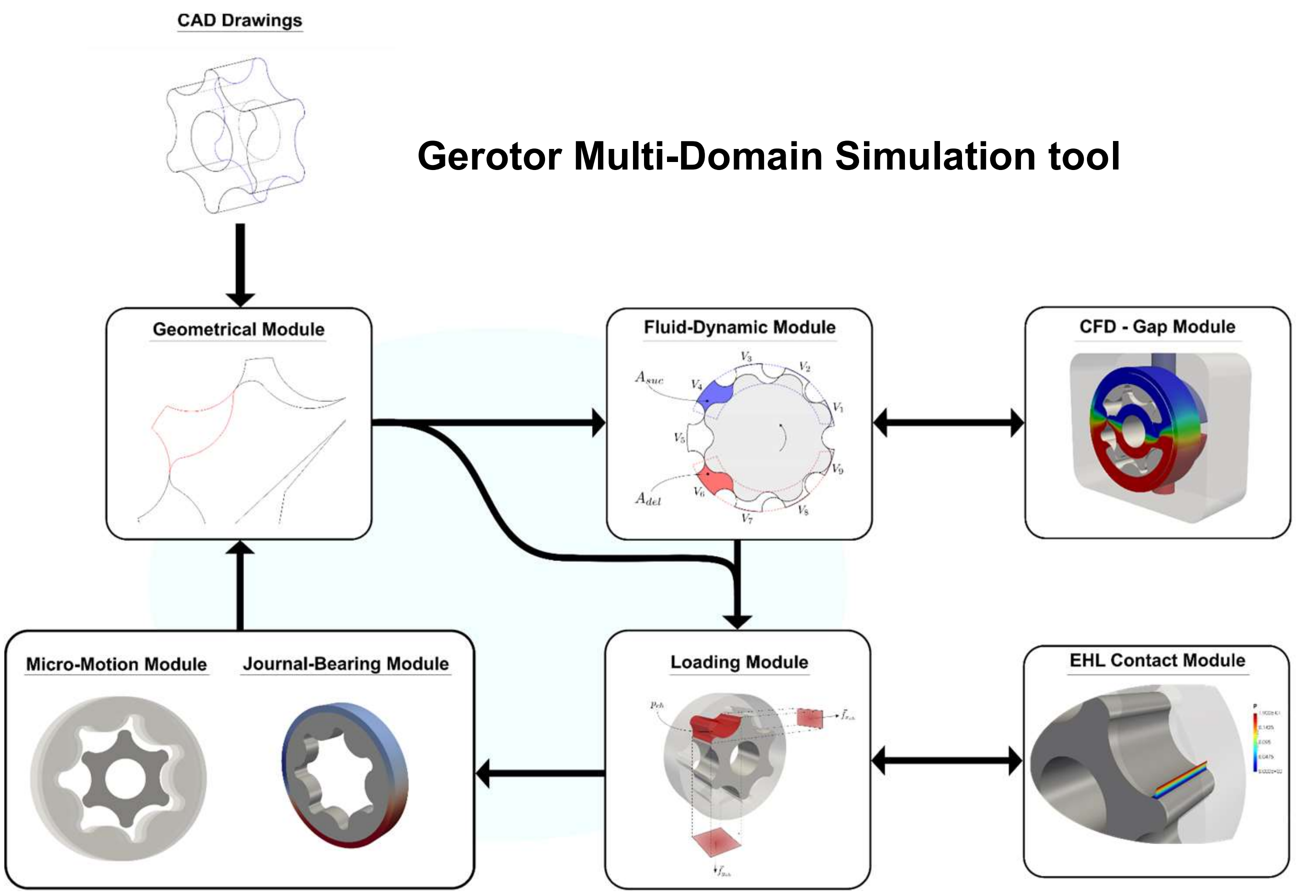






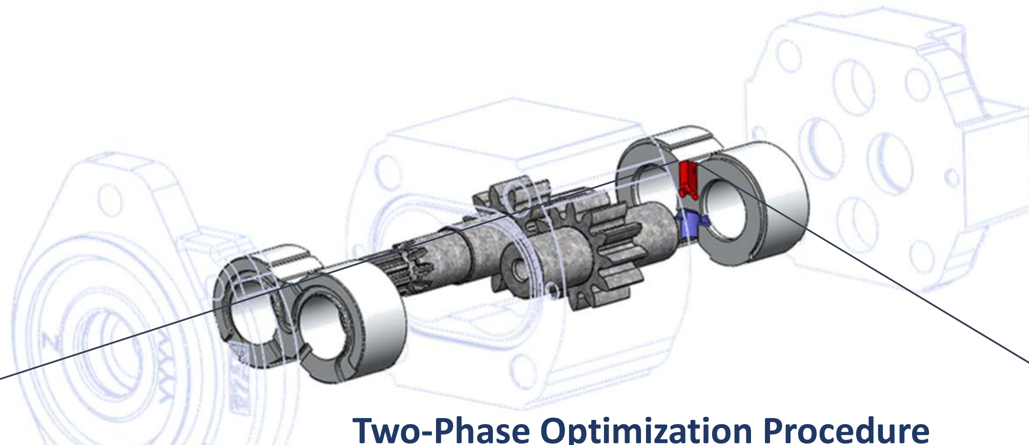
Modeling approach

Modeling



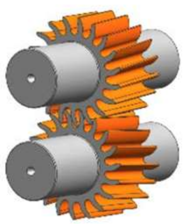
Design approach

Virtual prototyping



Two-Phase Optimization Procedure

LEVEL I – Gear Optimization

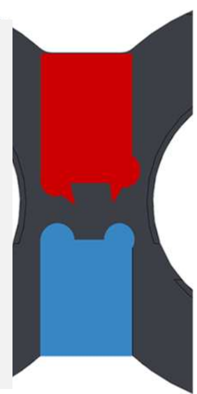


Finds the gear profile satisfying gear and meshing constraints

Objective Functions

- overall hyd. Efficiency
- el. motor efficiency
- total volume
- noise emissions
- localized cavitation
- int. pressure peaks

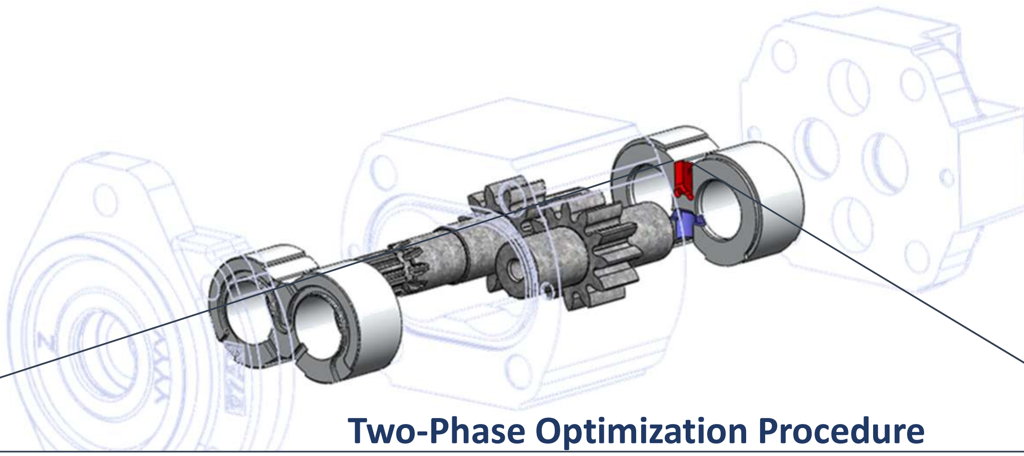
LEVEL II – Groove realization



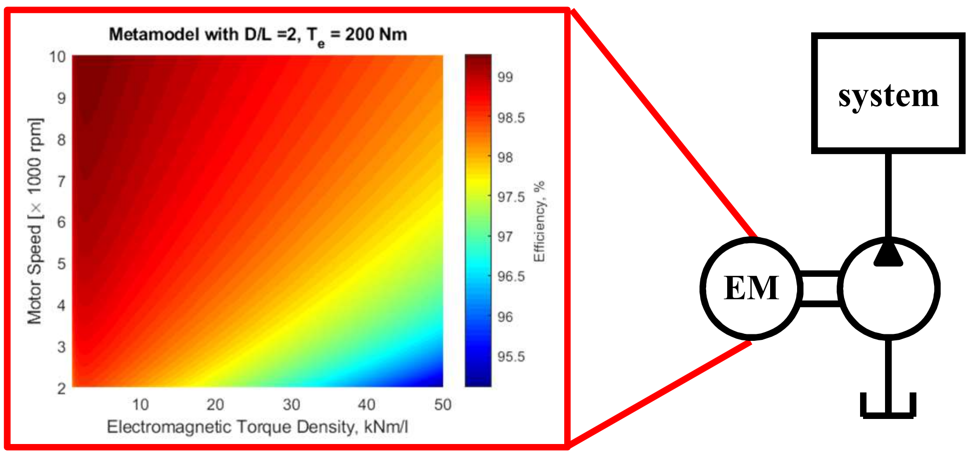
Finds the optimal timing for a given gear profile

Design approach

Virtual prototyping



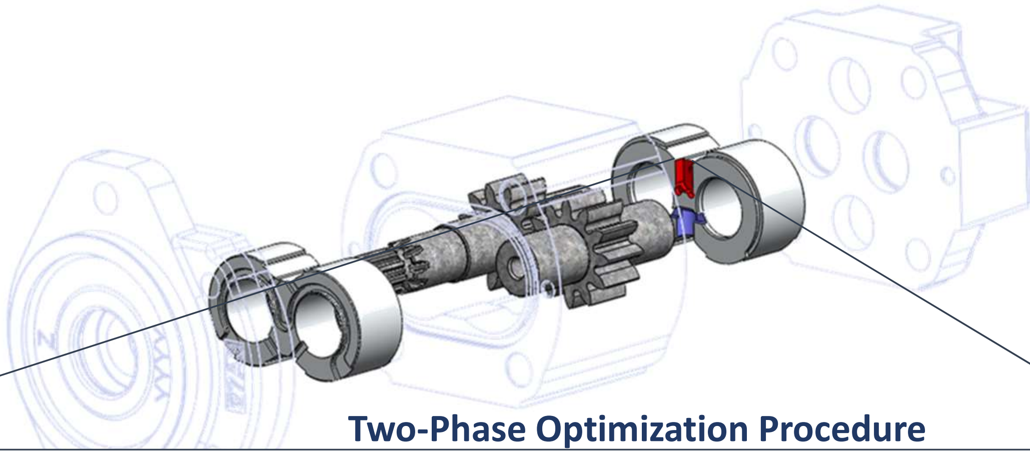
Two-Phase Optimization Procedure



Sudhoff S., Raj S., 2018, *Metamodeling of Rotating Electric Machinery, IEEE Transactions on Energy Conversion*, 2018, pp. 1–1., doi:10.1109/tec.2018.2793160

Design approach

Virtual prototyping



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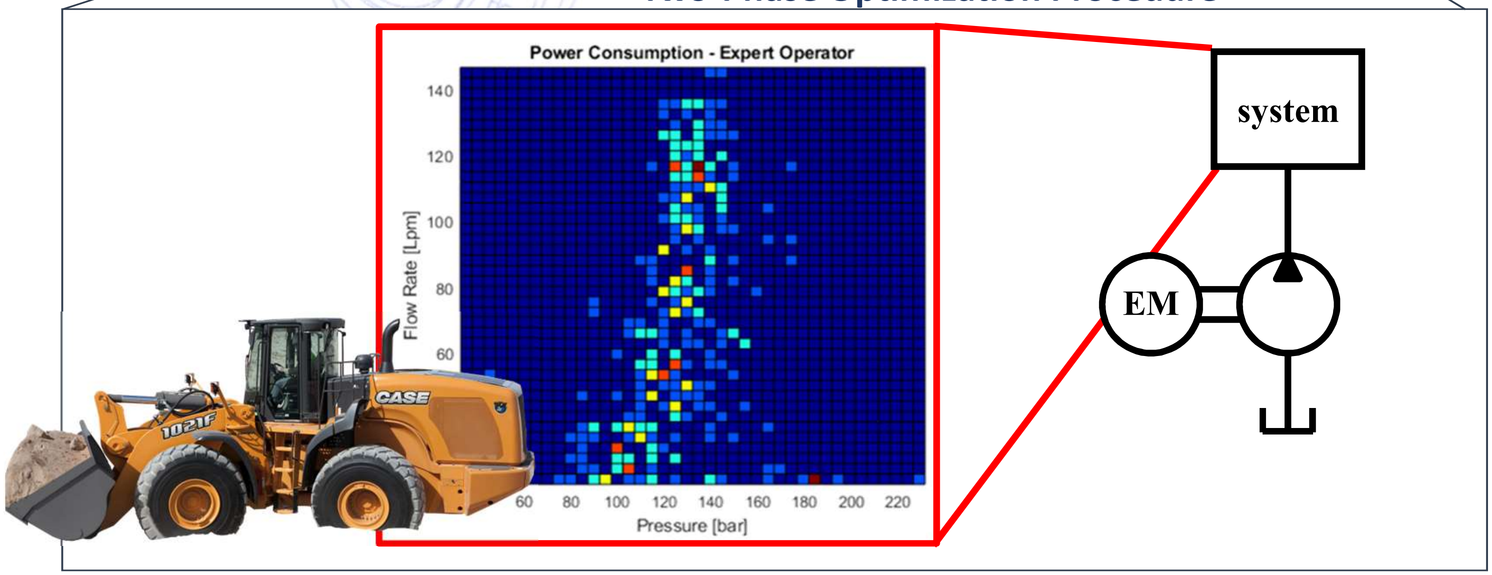
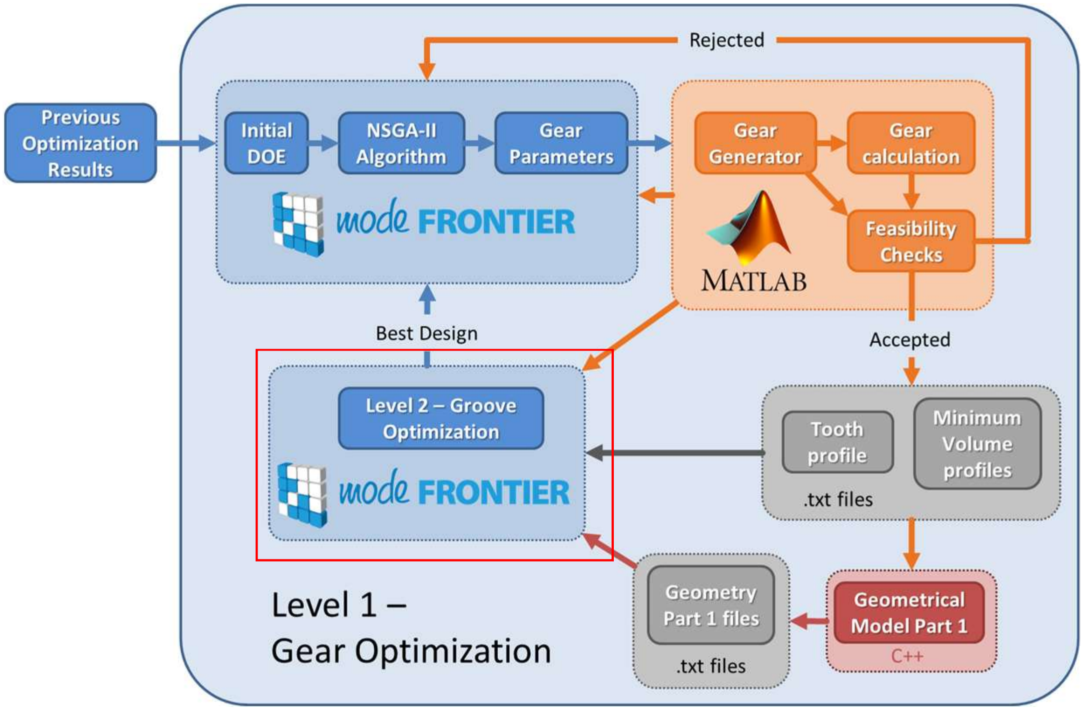
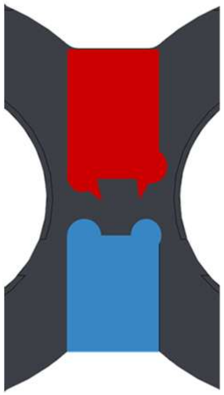


Design approach

Virtual prototyping





DOE project - workplan

Objective 1 (O1). 4-quadrant EH hydraulic unit.
Design study depending on the target power. High voltage and low voltage solutions.
Fabrication and testing of prototypes targeting the reference applications.
Tests will be performed as stand-alone, for model validation purposes, on EHA (O2); and on the reference vehicle (O3).

Objective 2 (O2). Individualized EH system.
Development of self-contained EH modules. Definition of the layout and local control structure of the hydraulic circuit to allow for both throttle-less and independent metering modes, thus guaranteeing fine regulation capabilities with maximum energy efficiency.
Fabrication, and Testing of three prototypes

Objective 3 (O3). Technology demonstration.
To establish proof of concept, the team will demonstrate the integration of the EH Units (O1) and EH Modules (O2) using reference off-road vehicles. O3 formulates a *supervisory controller* for the EHAs, the ICE, and the electric battery that permits optimal energy efficiency. Different energy-management strategies will be formulated: fixed-point ICE operation, to promote ICE downsizing potentials; *aggressive setting*, to increase productivity; and *zero emission* mode (to facilitate actuator operation with the ICE turned off).

DOE project - workplan

Period 1 (12 months) Preliminary Design	Period 2 (12 months) Initial Implementation	Period 3 (12 months) Technology Demonstration
Description		
numerical analysis for the EH units (O1), as well as for the individualized system (O2). Identification of the best design solutions and the related performance parameters (energy efficiency, power-to-weight ratios, costs). Determination of the requirements of the electric system of the overall vehicle considering the typical duty cycles for both reference vehicles.		
Milestones		
A. Definition of demo vehicles (O3) B. EH-unit, EGM (O1) C. EH-unit, internal gear (O1) D. EH module layout (O2)		
Go/No Go decision points (to proceed with the planned activities of the next project period)		
GNG1. EH module simulated performance (has to be above 0.8 at best points) GNG2. EH unit simulated performance (proven feasibility, efficiency never below 0.7 in the operating range, 0.9 at best efficiency points)		

Conclusions

- Electrification as a clear fluid power trend. New systems, components and design methods are needed
- This DOE founded effort partially reflects the vision of the Team (Purdue, Bosch-Rexroth, Case New Holland Industrial)
- The research approach is based on EHAs. Where new 4-quadrant EH pumps are designed
- Internal and external gear pump technology will be investigated
- A reference off-road vehicle was selected and instrumented for baseline tests
- Optimization procedure for the 4-quadrant EH units finalized

Thank you !

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