Electrification of Hydraulics Opens New Ways for Intelligent Energy-Optimized Systems

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Based on different motivations and driving forces for the electrification of hydraulics, this paper introduces and explains the solutions and basic principles used for increasing the energy efficiency by electrification. The following chapters explore these solutions and principles in depth. The key success factors for the electrification of hydraulics are intelligent energy management and appropriate energy storage type and size. Particular attention is paid to the energy storage systems giving an overview of their optimal application fields. The „Smart Energy Mode" energy management solution for industrial applications is then introduced. Afterwards, the Smart Energy System Design is explained by way of an industrial and a mobile example. The paper concludes with a remark concerning the current needs of automatic linking of different model-based tools. This ensures the holistic approach required in this context.

Keywords: Energy management, electrification, variable-speed pump drives, simulation, sizing, energy buffer
Target audience: Mobile Hydraulics, Mobile Applications, Mobile Working Machines, Industrial Hydraulics, Industrial Applications, Marine-Offshore, System and Machine Design Process

1 Introduction

The electrification of industrial hydraulics was initiated in the context of specific product developments in the past decade /11/. Electro-hydraulics combines the advantages of both technologies, that is to say the energy density of hydraulics plus the energy efficiency, noise behavior and easy commissioning of electro-mechanics. Today /10/, the electrification of industrial hydraulics is furthermore advanced by the following technological trends:

- Energy management and efficiency
- Industry 4.0 and
- Condition Monitoring (CM).

On the other hand, the trend of electrifying mobile machines comes from the electro-mobility in the automotive industry. However, the first steps were already taken more than 20 years ago /9/. As regards this industry, an increasing public awareness can be observed in the market, in the politics and in the media. This awareness has caused more and more manufacturers of mobile working machines to engage in electric drive concepts. In this case, the focus is on the complete or partial electrification of the traction drive. Depending on the requirements, different performance classes accepted in the market become apparent. Today, they define the operating limits of the technology, but at the same time drive the developments of drive technology components toward increasingly higher performances.

The motivations and reasons for electrifying mobile machines are more diverse than in the case of the electrification of industrial hydraulics. Although the tighter emissions legislation is generally considered to be the main driver of electrification of mobile applications, the important driving forces in the energetic context are:

- **Increasing the energy efficiency** and consequently **reducing the energy consumption, energy and fuel costs** are the main driving forces of electrification in most of the mobile applications.
- The electrification provides several options for intelligently exchanging energy and for integrating the energy storage media to buffer energy and cover the temporary power peaks. This allows the **diesel engine to be downsized** and thus allows the **costs for fuel to be reduced**. According to the performance class, the downsizing can be of higher relevance for compliance with the emission standards and the allowed emission values. In many regions, extensive exhaust aftertreatment is mandatory for a motor power of 19 kW and above. Due to downsizing, in some cases this aftertreatment will not be necessary anymore. The weight reduction of the diesel engine caused by downsizing is mostly or partly compensated by the additional electrical components, such as energy buffers.

In addition, one has to mention the requirements of **eliminating local emissions** for applications underground or in enclosed buildings, **reducing noise** of municipal vehicles for night-time work, **spacial machine design flexibility** for machines with foldaway attachments and a high **control quality**, as well as the requirement of **oil-free** machines /15/.

Electrification usually leads to hybrid machines. In the majority of applications, the axes of high power density, i.e. the working axes, are implemented as electrohydraulic axes, and those of lower power density are implemented as electric axes, e.g. secondary functions or the traction drive in mobile applications. The technological advantage with regard to energy efficiency primarily lies in the coupling of multiple axes in the DC bus group (DC grid). This increases the flexibility for engineering of energy-optimized system solutions. Electric main power split opens up new paths for transferring existing low-loss electric drive technology solutions that the chapter below will deal with.

1.1 Solutions and basic principles for increasing the energy efficiency by electrification

The primary measures for increasing the energy efficiency by electrification can be divided into four groups:

1. **Efficient components and systems, i.e. minimizing the losses** on the component or axis level; the following measures are used in accordance with the application:
   a. Replacing the loss-dominated valve controls by variable-speed pump controls which in turn allows „power on demand" solutions to be used
   b. Generally using low-loss components
   c. Energy-oriented operational optimization by displacing the operating points to the ranges of optimal, higher efficiencies, or by optimizing the working cycles with regard to energy consumption, e.g. by optional deceleration of cycle parts
   d. Controlling the reactive current eliminates the losses caused by it in the mains connection phase within the drive system. The mains supply is utilized in the best possible way and only the active power is transmitted. /1/
   e. Controlled regeneration: Maintains the power factor on a very high level, causing the reactive power to be reduced on the mains side and thus the feeding back processes to the mains to be optimized. /1/.
2. **Energy recovery and storage** implies intelligent management of energy amounts obtained from generator operating mode phases and it is a key issue for electrification. Decisive is application defined recuperation potential during the work cycle (e.g. down-stroking presses, tele handler) and choice of the proper energy storage unit corresponding to the energy amounts to be stored. Energy optimization in this case takes place on the higher system or machine level, or within a DC bus group (a DC grid). This generally includes

a. demand-based electric energy distribution within a DC bus group incl.

b. energy buffering in an appropriate energy buffer, and

c. optimized supply and energy regeneration from the, and to the mains[1].

3. **Smart Energy System Design:** The potentials for energy saving on component level are very limited. Therefore, an intelligent and application-oriented selection and combination of different measures for increasing the energy efficiency is the deciding factor for energy-optimized measures contribution. A holistic approach is required at least on the system level and mostly on the machine level to achieve the relevant energy-optimizing steps. In most cases they result from the accumulation of multiple optimization measures. In view of today's highly complex drive technology and machines, these measures can rarely be taken without the help of professional model-based sizing tools /2/, /6/ and appropriate commercial simulation tools. These tools are used during the entire, often iterative engineering process /10/ that involves the following steps:

   a. system concept design including the energy management concept, use case definition for energy storage and quantification of energy amounts to be stored

   b. deriving the requirements on the components

   c. energy-efficient components selection and sizing incl. the energy storage unit

   d. functional development or selection of control and energy management functions

   e. functional verification by simulation

   f. determination and quantification of improvements with respect to the referred conventional drive solution[2]

   g. optimization, if necessary

   h. price-performance ratio comparison with respect to the referred drive solutions; solution decision and technical implementation

4. **Energy on Demand**, i.e. energy usage according to consumer needs, stand-by mode in inactive cycle phases (see item 1a) and control routines ensuring need-based energy consumption.

The hybrid drive technology is today in transition. The trend toward electrification cannot be stopped and increasingly picks up speed. For many applications, however, there is a drive-related technology performance limit. This performance limit has to be constantly determined, especially because it keeps being expended in the direction of higher performances due to ongoing developments in the electric drive technology. It is therefore immensely important to apply the engineering process described above also to conventional reference systems or machines. In this way the value contribution of the selected system solution is quantified and ensured for each application.

2 Energy management solutions for the electric drive technology

The existing energy management solutions for the electric drive technology emerged from the following industrial requirements:

- Minimizing the power peaks of supply from the mains
- Minimizing the power dissipation
  - in all components, particularly the power to be dissipated in the braking resistors; ideally braking resistors should not be required
  - in mains connection and supply unit
- Storing energy amounts obtained from generator operating mode
- Ensuring the power supply in the case of mains failure or unstable line conditions
- High power density
- Utilizing high motor speeds that require high DC bus voltage
- Independence of mains voltage that requires controlled DC bus voltage
- Reducing the mains load - requires using energy buffers to avoid frequent switch between in feeding and regenerative mode

[1] In the case of industrial applications, and should be avoided if possible.
[2] for this solution is in most cases the same engineering process necessary, unless it is based on a known conventional system for which the first 2 steps are not required

Figure 1 contains an overview of the basic energy recovery solutions. These solutions are: the energy distribution, energy buffering and energy regeneration on demand. That is to say the recovered energy can be exchanged between multiple axes within the DC bus group, depending on the demands, buffered in a suitable energy buffer or regenerated to the mains. The latter, however, should be avoided if possible.

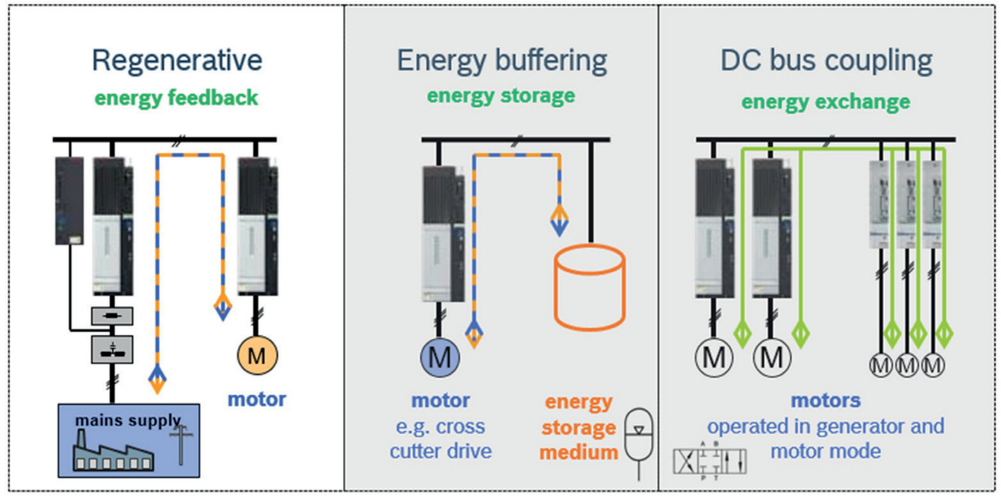

Figure 1: Energy Recovery Solutions Overview

In most of the applications, the energy flow control is physically implemented as a power management. Additionally, the energy distribution on demand in some solutions results from active or passive DC bus voltage control or energy control /4/. The active DC bus voltage control is implemented according to IEC 61131 on a drive-internal PLC platform (MLD) of the IndraDrive controllers. The passive DC bus voltage control is implemented in the firmware of the IndraDrive supply units and will be explained in detail in the following chapter.

2.1.1 Smart Energy Mode /4/

Regenerative supply units /4/ with Smart Energy Mode reduce current and power peaks on the mains side. The Smart Energy Mode limits the maximum device current to the 1.1-fold value of the nominal current. Furthermore, according to the machine-specific process, the recuperative energy amounts obtained are basically stored in a suitable energy buffer in the DC bus and returned to the corresponding consumers according to their energy needs

(Figure 2). Primarily, capacitive and kinetic energy buffers were used (for details see chapter 3). From the technical point of view, however, it is possible to use other energy storage types.

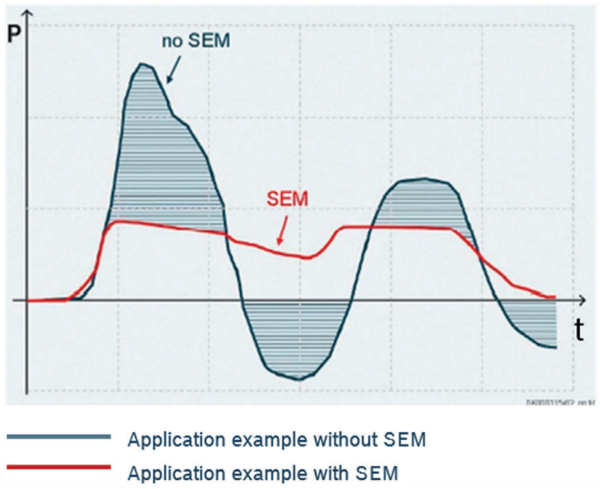

Figure 2: Mains power with or without Smart Energy Mode (SEM)[3]

Depending on actual DC power and DC voltage the Smart Energy Mode distinguishes 4 operation cases that are illustrated in Figure 3 below: motor and generator operation mode, each of them in feeding and regenerative.

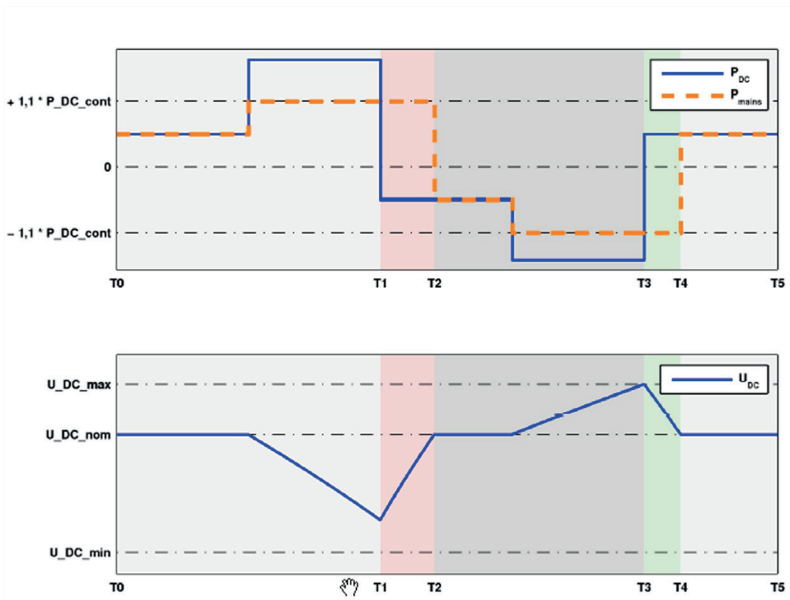

Figure 3: DC power and DC voltage progression curves for different operation cases

Only the in feeding motor operation mode is briefly explained below. The correlations for the other operation cases can be easily derived corresponding to Figure 3.

[3] Hachured areas mark the buffered/boosted energy.

If the conditions (1) and (2) have been fulfilled, the installation or machine is in the in feeding motor operation mode:

$$P\_DC(t) \geq 0 \quad (1)$$

$$U\_DC(t) \leq U\_DC\_nom \quad (2)$$

The maximum DC bus voltage correspond to the nominal DC bus voltage. If P_DC(t) > 1.1 × P_DC_cont, the DC bus the used energy buffer (e.g. capacitance) has to supply the additional energy. The DC bus voltage may not fall to the mains peak. This means that the DC bus energy buffer has to have at least the energy E_DC_min. For details see Figure 3.

Conventional solution	Solution with the **Smart Energy Mode**
High pulse load on the mains side by cyclically punching head acceleration and deceleration Performance: 1060 strokes/min	Clearly reduced mains load Regeneration is avoided by use of energy buffers Performance: 1060 strokes/min unchanged
Average connected load	
7.3 kW	5.1 kW, i.e. -30%
Maximum power	
53 kW	22 kW, i.e. -58%

Simulation results

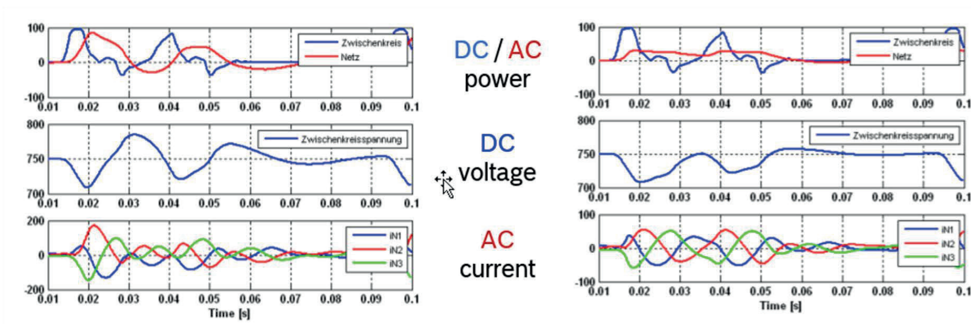

Table 1: Exemplary implementation in an fully electric Trumpf TruPunch 3000 punching machine

Table 1 shows the exemplary implementation in an industrial all-electric machine.

The characteristic aspects of this energy management are:

- The DC bus voltage is not constant, but fluctuates on a high level within a certain tolerance band.

- The DC bus voltage remains independent of the mains voltage within an extended voltage range.
- Energy buffers in the DC bus are utilized in the best possible way.
- The energy can be recovered at a high power factor ($\cos(\varphi) \approx 1$); this minimizes mains disturbances and reactive power on the mains side

Mains supply units with Smart Energy Mode have the following effects:

- Reduction of the power consumption from the mains by up to 30%
- Reduction of the pulse load in the mains by up to 50%
- Reduction of power losses in the control cabinet

This provides the following benefits:

- Reduction of the energy consumption and energy costs
- Usage of smaller components in the mains connection and for cabinet cooling
- control cabinet space saving

3 Energy storage systems

Energy storage systems are very diverse with regard to the product portfolio available in the market, the basic principle and the performance. Many citations provide a good overview, e.g. /14/. The energy storage systems that are suitable for the electric and electro-hydraulic drive technology target applications due to their properties are shown schematically in Figure 4. This overview shows that as compared to the hydraulic ones, the number of energy buffers within electric power split is much higher, which allows a wider combinational matrix. This illustrates the new energy storage possibilities for hydraulics which are opened up by their electrification. Apart from that, the possible solutions of hydraulic power and energy distribution basically entail higher losses.

Figure 4 contains rough recommendations and notes for the use of different energy storage systems in the drive technology. Apart from that, it has to be mentioned that the electro-chemical energy storages also cover a large variance with different technical features, particularly if you include hybrid energy storage in the consideration. In this connection, different Ragone plots may provide manageable support. The terms and definitions for rechargeable batteries are specified in DIN 40729.

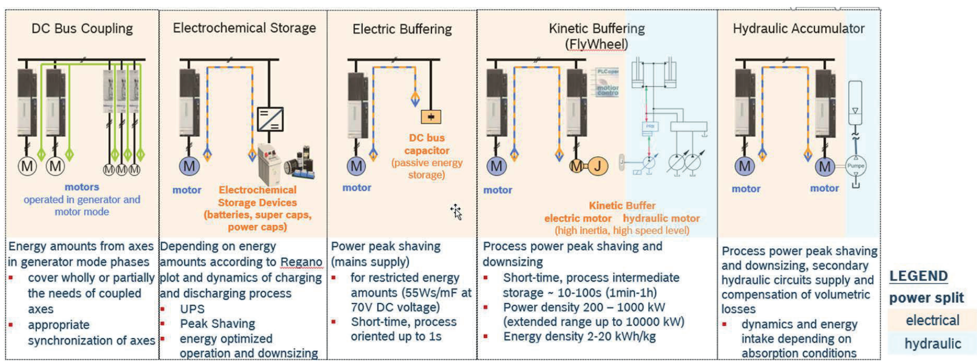

Figure 4: Overview of the energy storage solutions suitable for electric and electro-hydraulic drive technology

For the electric power split the lithium-ion and lithium-ion capacitors (LIC batteries) as well as super capacitors (UltraCaps) and batteries are the most interesting ones of electro-chemical and hybrid batteries. The further differentiation between them can be done according to the application based on their performance.

3.1.1 Application areas, comparison and sizing criteria for the energy storage

The most important selection criteria for a suitable energy storage are:

Use case	Technical performance
• Uninterrupted power supply (UPS), • Coverage of power peaks (peak shaving), • Ensuring an optimized, i.e. minimized energy consumption or component downsizing by including recuperative energy amounts obtained • Emission-free supply of electric or electro-hydraulic working axes	• Amounts of energy to be absorbed • Storage duration and self-discharge • Cyclic or needs-based energy absorption and supply • Required service life • Dynamics of the charging and discharging processes • Environmental conditions • Maximum weight allowed • Inflammability

Table 2: Selection criteria for energy storage

The common energy storage comparison or design characteristics are:

- **Energy density [kWh/kg] or [kWh/l]:** Energy amount that can be stored per weight or per volume. This characteristic is decisive for the solution dead weight, i.e. for its degree of compactness and thus a very relevant technical characteristic for mobile machines.
- **Power density [W/kg] or [W/l]:** describes how much power per volume or mass can be taken from the energy storage medium. This characteristic specifies the dynamic behavior (acceleration ability).
- The **service life** of most energy storages[4], particularly of electro-chemical ones, is limited by degradation processes and specifies the number of charging-discharging cycles after which an energy storage only has a certain rest charging capacity (generally 80% of the nominal capacity).
    - Service life in operating hours[5] is used in the case of systemic sizing and has to be converted according to the underlying cycles. In the ideal case, the service life of the energy storage used should approximately correspond to the service life of the drive systems used (~30,000 h) or to that of the weakest component in the residual system.
- **Efficiency** as characteristic describes the ratio of the achievable energy to the energy used for charging. Like all components, every storage system has physically inherent losses, as well; consequently, their efficiency is a relevant characteristic within energetic optimization considerations.

4 Exemplary implementations of Smart Energy System Design

The Smart Energy System Design is explained in more detail using two exemplary implementations that illustrate today's necessity of holistic approaches and the integrated, closed linking of model based sizing and simulation tools.

[4] Except for kinetic buffers
[5] With most battery types, 1,000 to 2,000 cycles are now guaranteed. Ultracap up to approx. 1,000,000 cycles. For capacities, the market assumes or expects a service life of approx. 8 years.

4.1 Sizing and simulation of a forging press

The first example focuses on an engineering process and the project planning of an industrial installation.

The initial information comprises the load profiles of the working axes and the requirements in the form of concrete technical performance characteristics. The first process step is the system conception and system design based on this information, followed by the first components selection and sizing. Due to the restricted initial information and missing tools for an automatic selection of the components, this process step is often carried out by using very simple calculation tools e.g. self-written Excel, MATLAB or Simster /3/ calculations.

After a concept[6] (see Figure 5) has been fixed and the related components have been designed, simulation models of included axes can be created. In this way, the concept of overall system or overall installation is simulated with application-specific cycles, checked for feasibility and optimized according to the concrete requirements.

In the ideal case, a positive result is immediately achieved. However, often several alternative solutions are checked or the process iterates some loops at this point. From the positively evaluated final result, the load profiles are then derived for electrical components and based on this, the final drive component selection is made using commercial sizing tools based on wide product database /2/, /6/.

In this concrete case, several energetic optimization solutions have been created and implemented for hydraulic main axes /8/, /12/, /13/. For process-inherent reasons, down-stroking presses offer large recovery potential regarding the potential and/or braking energy from the lowering movements of the upper ram. The recovered energy is supplied into the DC bus by electro-hydraulic energy conversion and fed back into the mains. The energy recovery from the decompression and the suspension of the press frame happens in the same way. Due to the three-chamber cylinder construction /8/, re-suction from the tank via the filling valves is omitted in rapid movement; this prevents a power loss of up to 10kW. Apart from that, the press standstill is held by safety valves. The servo motors of these axes are then also in standstill and only the secondary axes for the work piece handling are active (power on demand).

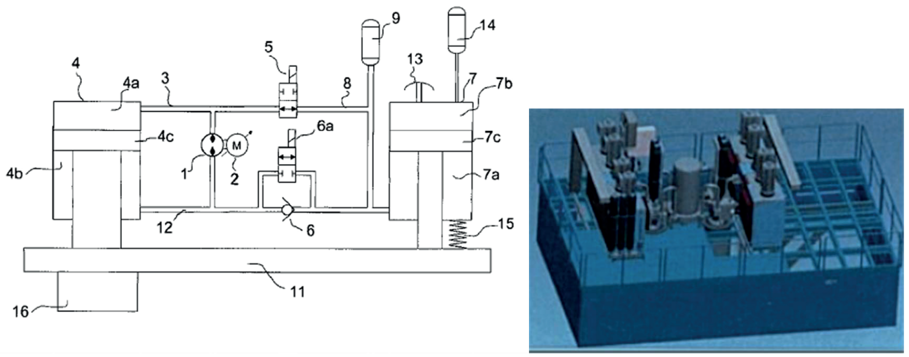

Figure 5: New hydraulic concept for 20 MN forging press (ring blank press) /8/, /13/

The sizing tools referred above actually does not support the sizing of supply units; the latter are currently sized either by use of simple, common sizing tools or using simulation models[7] in an iterative and half-manual manner. That is to say in the next sizing step, the entire DC bus group (Figure 6) incl. available simulation models of the Smart Energy Mode, energy and kinetic buffering module, which are often modeled separately, but in the same simulation environment. The inputs for these partial models are the load profiles in the form of power or torque and speed progression curves over the time. They are either available as result of individual axis simulations or as customer specification. This process step results in

- the selection and/or dimensioning of energy buffer and supply unit
- the DC bus power[8] on the basis of which it is then possible to calculate the required maximum and effective mains current for the given mains conditions.

Based on the determined load profiles, the cooling of the control cabinet and the motors is also designed and sized. The cooling concept is a fundamental part of the system concept. The cooling is on the one hand an important boundary condition to ensure perfect thermal operating conditions and thus the service life of the components concerned. On the other hand, the cooling design is also part of energetic and supply-related considerations for the overall system and also an energy efficiency indicator for concerned components in the relevant application case.

The control cabinet cooling consists of air cooling and water cooling. The required cooling power for water cooling for this installation is about 20 kW and that for the air cooling about 7 kW, which will dissipate a control cabinet power loss of about 27 kW.

The motor power loss to be cooled can be calculated in different forms and here amounts to 3.62 kW per motor. It can, for example, be calculated from efficiency maps on the basis of the effective power (and/or the effective torque and the average speed). Another possibility is the calculation using the calculation formula for the main losses, i.e. the speed-dependent iron and the current-dependent copper losses that can also be included in the simulation models. In detailed considerations, extensive loss models are moreover implemented in the simulation models.

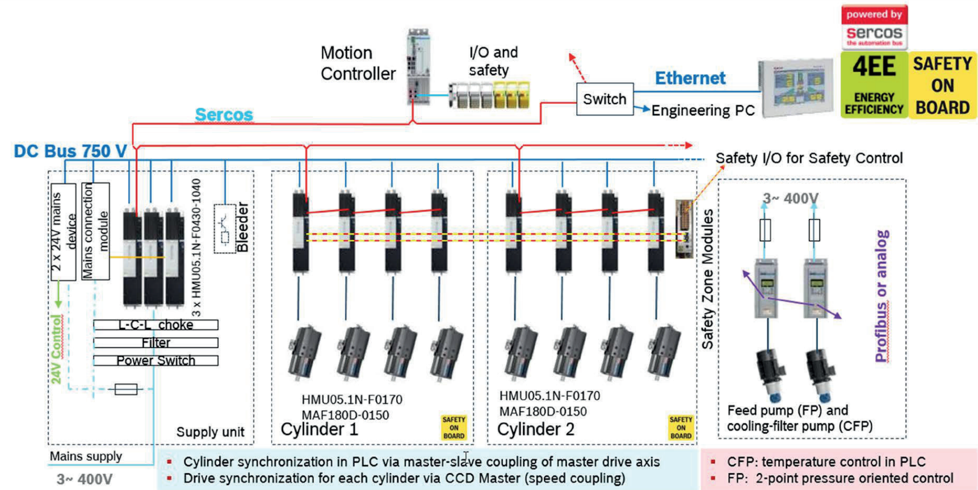

Figure 6: DC grid drive solution for a 20 MN EcoPlant forging press (ring blank press)

Today, the engineering process described here is carried out in an open linking of model-based tools by different technology experts.

4.2 Development of an electrical traction drive for mobile working machines

The Figure 7 shows the principle electrification system solutions for mobile applications, more precisely for their traction drive. The second example refers the hybrid diesel – electric solution and is shortly explained below (Figure 8).

[6] or several alternative concepts
[7] decoupled but in the same simulation environment
[8] Total power in the DC bus (8 motors) is 1,252 kW as peak for 11.2 s and effectively 330 kW with a cycle time of 64 s

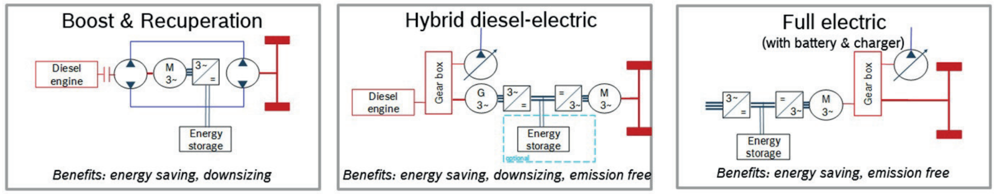

Figure 7: Electrification steps – traction drive system structures

4.2.1 Characteristics of electrified drive train for mobile working machines

This development is characterized by a mixture of new developments and transfer of the available know-how from the existing solutions for industrial applications. This also comprises an adjustment development of the existing industrial product portfolio of electric drives /15/ due to specific requirements for mobile applications (e.g. environmental conditions).

Energy recovery and storage are the key issues leading to the main energetic benefits of electrification, i.e. downsizing and reduction of energy/fuel consumption. The target applications are identified according to simulation based estimation of these benefits for a reference working cycle. The latter is deciding in terms of quantifying of energy amounts which can be recuperated from breaking operations and boosted in accelerating operations. Based on these energy amounts the energy storage units and all drive components are chosen and sized. Furthermore, the system weight and price can be calculated. Opposing the energetic benefits together with technical performance at one side and calculated price and weight at the other side leads to decision, if the electrification of drive train is worthwhile for the application of interest. At this point is to be mentioned that beside intelligent energy management the critical technology breakthrough factors are sizing and prizing of energy storages. From this point of view commercial sizing tools for different energy storage systems are missing and required.

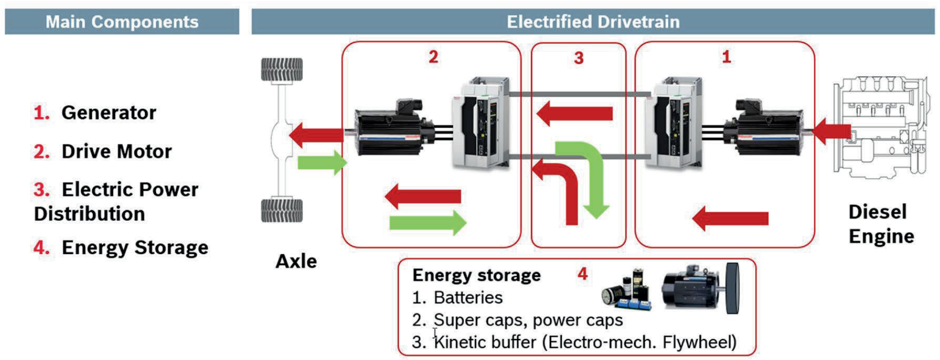

Figure 8: Basic system design of an electric traction drive

4.2.2 Development process and tool chain for electrification of drive train for mobile working machines

This example focuses on the simulative-methodical approach with different development phases in the electrification of traction drives for mobile machines.

As opposed to the presented example from industrial hydraulics, the underlying process here comprises a deciding, complex and extensive step regarding the development of the control and energy management functions. In the concept phase, these control functions are perfectly simulated with a "desired behavior" in order to enable the simulation of an overall system concept. In this way, the requirements on the control and energy management functions are defined automatically within the scope of the concept phase and at the highest level.

Another difference to the previous example is a more distinct integration of the simulation tools stretching across the process up to the final point of the implementation, i.e. to the automatic code generation and the test. The tool chain is shown in Figure 9.

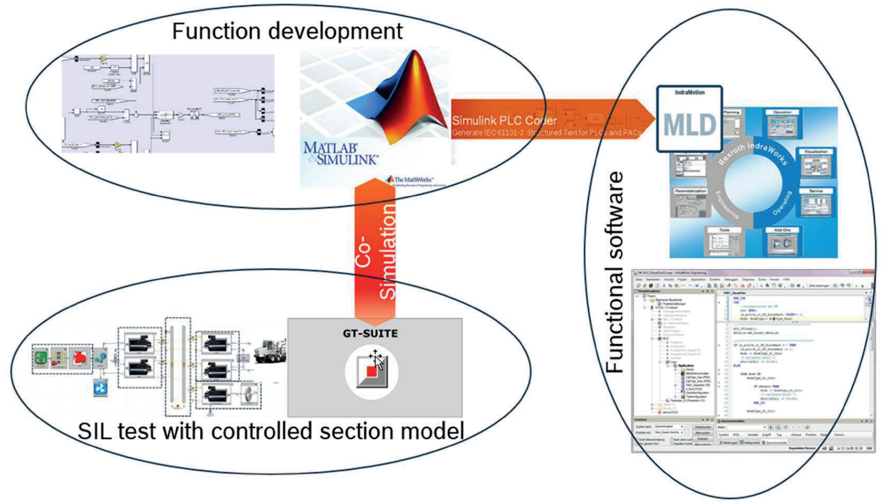

Figure 9: Tool chain for sample development of an electric traction drive

One exemplary result from the concept phase is shown in Figure 10 and illustrates a certain granularity of energetic optimization steps that are carried out and necessary.

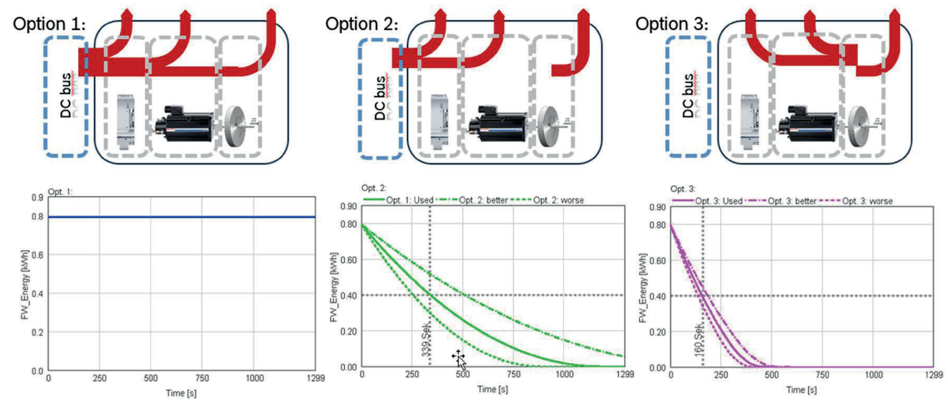

Figure 10: Kinetic Buffer operating modes analysis for one typical driving cycle[9]

Figure 10 shows the simulation results from the examination of different idle operating modes of the selected kinetic energy buffer (FlyWheel). In this simulation three operating methods have been examined and evaluated:

- <u>**Option 1: Constant speed:**</u> with this option, all losses are covered by the DC bus and thus, charge retention is ensured. One related disadvantage is that it may be necessary to generate the DC bus power with bad efficiency. This option is necessary for mid-/long-term storage.

[9] Curves „better" and „worse" are defining the tolerance band for self-discharging process curve due to possible unknown design parameters variance.

- **Option 2: no mechanical power at the shaft** (or torque is 0 Nm) results in reduced DC bus power which may possibly have to be generated with bad efficiency. This option is the appropriate one for mid- or short-time cyclical (dis)charging.
- **Option 3: DC bus power is zero:** with this option, all losses are dissipated within the Flywheel. This option is characterized with the lowest "half-life" time and hence appropriate for short-time cyclic (dis)charging.

The energetic value contribution of the electrification determined in the concept phase using simulation model with detailed loss models of all relevant components within the system for electrified drive train and this sample vehicle is: Reduction in fuel costs by up to 40% and downsizing of the diesel engine by up to 20%.

5 Summary and outlook

Due to its connection to a central electric power split, the electrification of hydraulics results in a high level of flexibility for optimal energy distributions and a considerable extension of the energy storing possibilities. The latter are the critical technology breakthrough factors, especially their sizing and prizing. An intelligent combination of different optimization solutions from a holistic system or machine point of view for hybrid machines and systems of today and tomorrow makes the remarkable energy efficiency increasing possible. In order for this to be successful, well-geared, cross-technology expert teams and an integrated platform or workbench for the closed coupling and linking of different sizing and simulation tools are necessary.

6 Acknowledgments

The product development, marketing and sales of the drive technology of "today and tomorrow" is faced with the challenges of increasing technical-informative complexity. Thus, cross-technology expert teams together with integrators constitute an indispensable creative and motive force /7/. At this point, we would like to thank to all our partners in such multi-technological projects and in this publication for very good collaboration and support.

Nomenclature

Variable	*Description*	*Unit*
E_DC	DC bus energy	[kJ]
P_DC	DC bus power	[kW]
$Pmains$	Mains power	[kW]
U_DC	DC bus voltage	[V]
	Subscripted Characters	
cont	the continuous value	
max	Maximum value	
min	Minimum value	
nom	the nominal value	
	Shortcuts	
SIL	Simulation In the Loop	

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