

New Software Generation for Greener Energy Efficient Mechatronic System Design & Analysis

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Abstract: In the world of simulation software, many different approaches are used to obtain accurate hydraulic circuit simulation. Most of these tools model components as a set of mathematical equations parameterized with mechanical and geometric data for each component. They are able to simulate in depth specific functions of a circuit, however it becomes progressively a more demanding task to simulate more complex and complete systems. One of the key elements of simulation software is its ability to model valve performance in terms of flow characteristics, pressure drop and flow force. This also holds true for pumps and motors where the knowledge of efficiencies is required to achieve realistic duty cycle behavior. In this paper, the chosen approach is to demonstrate the efficiency of modeling components using a software downstream design methodology by implementing readily available performance curves and other characteristics of hydraulic components and functions. This downstream method of modeling components ensures the reliability and accuracy of systems behavior based on manufacturer specific data and allows for fast simulation of complete virtual machines which is impractical to achieve by traditional upstream programming. The simulation of a complete hydraulic system delivers global validation and analysis capabilities that can also be exploited beyond the engineering design scope including maintenance diagnostics and training activities.

This paper will demonstrate that using Automation Studio™—a commercially available off-the-shelf drawing and simulation software tool that uses mainly downstream design—simulation data and OEM product information can be easily entered from a readily available hydraulic component vendor in order to create valves, pumps and motors for fast and accurate sizing and system simulation of a virtual machine. The ability to realistically simulate entire machines offers a unique capability to monitor, and study specific performance criteria such as: hysteresis, pressure drop, leakage, flow force, and other flow/pressure characteristics, power generation and transmission up to the full energy consumption at various operating conditions.

Nomenclature

P_e : Electrical power consumed by motor, W

Q_e : Electric reactive power, VAR

P_j : Power loss due to Joule effect, W

P_i, P_o : Mechanical power, W

ω_i, ω_o : Shaft rotation speed, rad/s

T_i, T_o : Torque, N.m

$\eta_e, \eta_v, \eta_m, \eta_o$: Electrical, volumetric, mechanic, overall efficiency

Δp : Differential pressure, Pa

P : Hydraulic power, W

T_f : Torque due to friction, N.m

μ : Coefficient of viscosity, Pa.s

D_p, D_m : Pump or motor displacement, m³/rad

τ : Forces (resp. Torques) applied on a body, N (resp. N.m)

1. Introduction

With current economic pressures, system designers are increasingly constrained to provide more demanding technical designs in less time. Also, rapidly increasing energy saving requirements add even more constraints that force designers into making difficult compromises. This often results in neglecting certain aspects of the product life cycle, either in

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design, validation, documentation, training, sales or maintenance.

In particular for the design and validation stages, a variety of tools exists on the market to help validate system design through simulation. Many simulation tools can be used to do upstream design by programming component internal attributes and physical phenomena. Although these methodologies can produce very accurate simulation results at the individual level, they require the system designer to have access to every component's internal physical parameter. This means that the designer must have a great deal of expertise in the specifics of each component. Since a global system involves many different elements, it would take a considerable amount of time and effort to calibrate and model a complete system. This also significantly reduces reusability of upstream-designed systems, which makes them prohibitively costly and complex when it comes to designing complete machines that involve several technologies.

Instead, a new trend of downstream design in the industry has been developing. It consists of having pre-modeled modules that are used as-is by the system designer.

This paper details the characteristics of downstream design as applied to a complete mechatronic system. Chapter 2 explains the concept of a virtual machine built using preconfigured catalogue components. Chapter 3 explains certain concepts involved in system design and shows some of the limitations of upstream design. Chapter 4 gives specific examples of downstream design using Automation Studio™. Chapter 5 concludes with some final remarks on the characteristics of both upstream and downstream approaches and shows the advantages of using modular design software like Automation Studio™ that allows combining technical design and simulation in one complete innovative tool.

2. Mechatronic Virtual Machine

Generally, speaking of Mechatronic Virtual Machine implies one of the two aforementioned approaches. For example, a lot of virtual reality software offer animated 3D models of a machine that can be realistically operated. However, most of the

time only a high-level global model of the machine is simulated and it does not take into accounts all the related technologies that impact its behavior.

In this paper, "virtual machine", means a complete simulation model, enhanced with a 3D visualization moving according to the real physical contributions of all the involved technologies.

Fig. 1 illustrates perfectly this concept of mechatronic virtual machine, where all the related technologies are simulated: electrical engineering, hydraulics, mechanics and control.

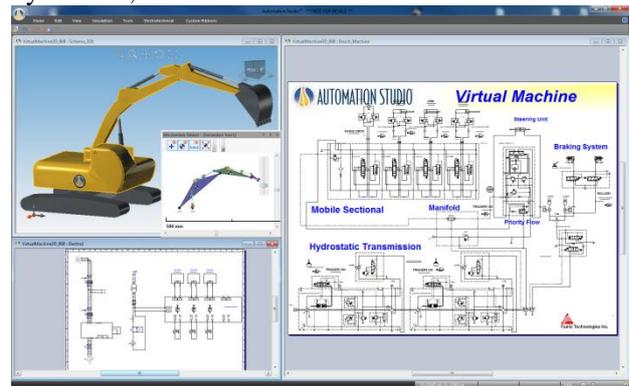


Fig. 1 Complete Mechatronic Virtual Machine

The presented machine is constructed using hydraulic components exclusively selected from component manufacturer catalogs. Moreover, the virtual machine is drafted using standard 2D representation the related technologies.

Automation Studio™ offers the possibility to model these machines using two types of libraries: either by using generic unit components that respect the ISO-1219 standard or by using a set of manufacturers' components, where symbols are exactly those used for their 2D drawing and where the technical specifications are already built in the components. Therefore the virtual machine is fully configured as and it is being built.

Moreover, this concept of virtual machine does not consist of a set of recorded results produced by an offline preconfigured simulation, but rather consists of an interactive live simulation where the evolution of the machine in time is monitored and acted upon live by the user. This means that it is possible for a virtual machine to be operated as the real machine would be. By modifying variable input generators, or by acting directly on some configurable components, it is

possible to dynamically modify parameters and to immediately observe their impacts on the simulation.

This latter point offers the possibility to do interactive tests, giving access to all possible operating conditions. Therefore it enables to perform very important analysis such as power analysis and energetic functioning consumption of all components, as illustrated in Fig. 2.

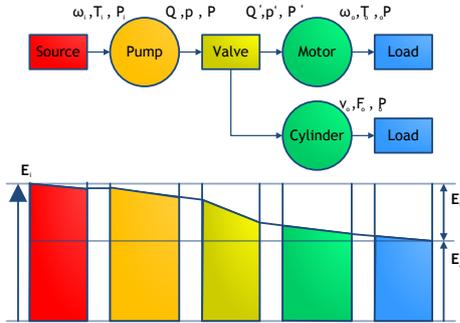


Fig. 2 Energy Analysis of a Complete Virtual Machine

Taken from [1], this graph shows, in the form of an energy balance, the losses in each active component of the machine, where power is transmitted. A complete simulation model of the virtual machine enables to realistically model each of these functions and subfunctions. And even if each of these analysis can be done independently, i.e. technology by technology using different and specific modeling and simulation tools or approaches, it is essential to note that all these analyses are macroscopically linked in the virtual machine, the output of a technology becoming the input of another, and vice versa.

In order to illustrate this multi-technological aspect of virtual machines, the next section reviews general models of the different technologies used in a mechatronic system.

3. Simulation Models

3.1 Electrical System

In a motion transmission system involving electrical power components, several elements can impact the overall efficiency of the electrical system. In a classical electric system, the following effects result in power losses:

- Switching element and conductor heating;
- Reactive Power transmission;
- Misc. effects.

Conductor heating is an inherent effect due to the resistive nature of conducting materials. As an illustration, the lost power can be quantified as

$$P_j = \sum R \cdot i^2$$

Where P_j represents the Joule resistive losses, R represents the resistance of an element and i represents the current flowing through it.

The minimization of Joule power losses is done both by designing low resistance elements (thick wires, low power consumption switching elements ...) and by reducing the transited currents. In order to maintain transit of the same power demanded by the hydraulic load, reducing currents implies raising the voltage levels.

Reactive power is power that is transited in the electric circuit without being transformed into work. This power transits unnecessary currents back and forth between the source and the load, thus creating extra Joule losses in the conductors.

As an illustration, this extra current, called Reactive Current can be quantified as

$$I_r = \sqrt{\frac{Q_e}{X}}$$

Where Q_e represents the reactive power and X represents the circuit's reactance.

The reactive power is related to the active power P_e (useable power) by

$$Q_e = P_e \cdot \sqrt{\frac{1}{\cos^2 \varphi} - 1}$$

Where $\cos \varphi$ represents the power factor.

So for a given active power, the minimization of the reactive current implies minimizing the reactive power which in turn implies maximizing the power factor by having it as close to 1 as possible.

Electric motors have an inherent reactive power consumption property, due to the magnetic interactions that are at the core of their function. Maximizing the power factor for a given motor is generally done by physically designing the motor to

have a high power factor under normal load conditions or by using capacitors to locally provide the reactive power needed by the motor, which would reduce the reactive current transmission over the complete circuit.

Other effects that impact electrical power loss can also be cited, like air gap, eddy current and harmonic power losses. These effects are due to the electrical components themselves rather than to their combination in the electric circuit.

Practically, air gap losses are minimized by designing high-efficiency components motors. The achievable efficiencies can reach upwards of 95% [6].

Eddy currents are due to varying magnetic fields that generate currents in the metallic core of the element. These are reduced by designing sheeted cores rather than solid cast cores.

Harmonics are generated by switching devices and by motors due to non-linear effects. These will tend to create high frequency current components that increase losses in the circuit. Those are usually reduced by adding low-pass filters in the circuit.

When validating the design of an electrical circuit, it is important to be able to render a realistic image of the energy balance of each stage in the transmission system. This is due to the fact that the overall efficiency, being the product of all the individual efficiencies involved, will tend to be impacted by any suboptimal element.

The efficiency of each element is difficult to model with a strictly parametric approach because the number of parameters and effect of each one on the overall behavior is very difficult to keep track of by the high-level designer. It is therefore more practical to provide pre-modeled elements with customizable curves that show the overall behavior of the component, including its efficiency profile, rather than providing a list of low-level parameters that are difficult to identify or quantify.

3.2 Hydraulic Components

When designing a hydraulic system, one of the main difficulties is having the full efficiency map based on various operating conditions. In this section, the main parameters that cause the losses in hydraulic components will be introduced. Using the general

equations presented here, the efficiency relationships can be developed based on multidimensional curves, as explain in section 4.

3.2.1 Hydraulic Pumps

The hydraulic pump will receive mechanical power from the source, either from a thermal engine or an electrical motor, and will convert it into fluid power

Because there are losses, the output Power can be described as follows:

$$P = Q \cdot \Delta p$$

Where Q is the output flow and Δp is the differential pressure between the inlet and the outlet of the pump. When we compare this output flow and the maximum theoretical flow Q_{th} from the input mechanical power, we realize that these components are not perfect. In a complete system analysis, we need to consider them to be accurate.

For a pump, we can establish the Power losses using efficiency parameters, volumetric and mechanic. The volumetric efficiency, related with the flow losses Q_l , can be expressed as follow:

$$\eta_{vp} = (Q_{th} - Q_l) / Q_{th}$$

It is fairly easy to get the theoretical flow from the input speed of the pump shaft ω_i and the displacement D_p of the pump as follow:

$$Q_{th} = D_p \omega_i$$

However, getting the flow losses is more difficult. The losses are caused by leakage, which can be internal and external to the pump. Even if the leakages can occur at many locations at the same time, since they are all of the same nature, we can generalize them using different flow loss coefficients C_{int} and C_{ext} . This leads to a relationship that is proportional to the displacement D_p and inversely proportional to the viscosity μ . This relationship can be expressed as follows:

$$Q_t = \sum_j Q_{t_j} = \frac{C_{int} D_p \Delta p + C_{ext} D_p (p_{op} - p_c) + C_{ext} D_p (p_{ip} - p_c)}{\mu}$$

This relationship can be simplified with some hypotheses on the outlet pressure p_{op} , case pressure p_c and inlet pressure p_{ip} as written in [1].

For the mechanical efficiency, we need to take into account different friction types that will be added to the input torque needed at a given pump pressure.

$$\eta_{mp} = T_p / T_i = T_p / (T_p + T_l)$$

With,

$$T_p = D_p \Delta p$$

The friction torque can be considered as the sum of four components:

$$T_l = \sum_j T_{l_j} = T_\mu + T_f + T_c + T_h$$

Where T_μ is the viscous friction,

$$T_\mu = \sum_j T_{\mu_j} = C_\mu D_p \mu \omega_i$$

T_f is the mechanical friction,

$$T_f = \sum_j T_{f_j} = C_f D_p (p_{op} + \chi p_{ip})$$

T_c is a constant friction caused by seals, and T_h is the hydrodynamic friction, which can be mostly neglected.

This brings us finally to express the overall efficiency as follow:

$$\eta_{op} = \eta_{vp} \cdot \eta_{mp}$$

If we refer to the equations established in that section, we can see that the efficiency of pump is a function of many parameters, but the exact relationships are difficult to obtain.

$$\eta_{op} = f(D_p, \Delta p, \omega_i, \mu)$$

Therefore, establishing a complete efficiency mapping in simulation is difficult using upstream programming, and the model built will only be accurate for specific pumps that have all the relationships created.

3.2.2 Hydraulic Valves, Lines & Others

The analysis of a fluid system based on complete fluid dynamics analysis is a tremendous amount of work. Also, since some mathematical models are difficult to establish and generalize for different operating conditions, energy losses in valves and lines in hydraulic design are often given by rules of thumb or empirical values. The goal of this section is not to cover advanced relationships such as in [7], but to establish an easy way to realistically consider pressure drops in hydraulic valves and lines.

In order to do that, we can approximate the pressure drop from two well-known relationships. If we consider a hydraulic component as an orifice, the following equation stands:

$$Q = k_v \cdot \sqrt{\Delta p / \rho}$$

Where k_v is the flow coefficient. The previous relationship considers a localized pressure drop. If the flow path is longer, then the following equation shows the relationship between the pressure drop, the geometry of the line, the fluid characteristic and the fluid velocity:

$$\Delta p = f \frac{L}{d_i} \cdot \frac{\rho (v_f)^2}{2}$$

Regarding the head loss coefficient f , its value varies based on the flow type - laminar, semi turbulent or turbulent - which can be determined based on the dimensionless Reynolds number and the Moody chart shown in Fig. 3.

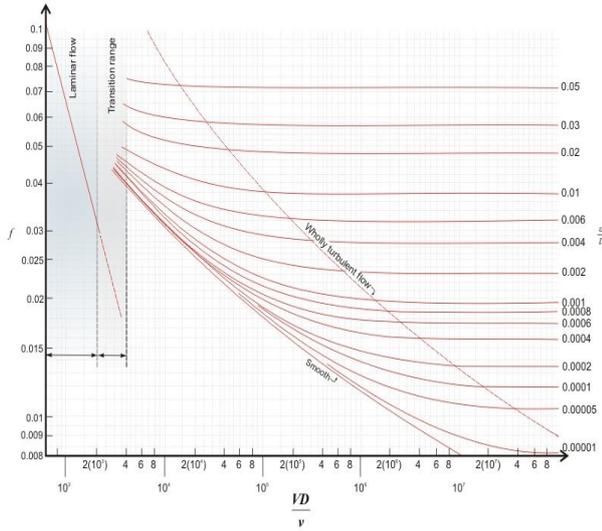


Fig. 3 Moody Chart

Finally, as the flow is pumped in the system, it generates pressure drops between inlet and outlet of hydraulics components. Even if this is desired for control and regulations applications, it produces also undesired energy losses that cannot be neglected in a complete analysis. And if the system contains many hydraulic components, equivalent and simplified relationships can be used to accurately obtain global pressure drop estimations in a system using localized and distributed pressure drop models or other simplifications based on other assumptions which can lead to even more simplified pressure drop relations as a function of the flow coefficient k_v .

3.2.3 Hydraulic Motor

For hydraulic motors, the model is similar to the hydraulic pump. The main difference is that the motor receives hydraulic power P' and converts it into mechanical power P_o , as described in the following equation.

$$P_o = \omega_o \cdot T_o$$

Mainly, the theoretical torque calculated with the input pressure and the motor displacement will be higher than the real torque output, since the output speed will be lower than the theoretical one from the input flow. Similarly for motors, a general relationship can be established for the overall efficiency.

$$\eta_{om} = f(D_m, \Delta p, \omega_o, \mu)$$

3.3 Mechanical System

Simulating a mechanical system actuated by hydraulics involves two additional aspects in the analysis of the complete system efficiency: power transfer among mechanically linked hydraulic components, and losses in the mechanical system proper.

3.3.1 Dynamic Model of a Mechanism

Because each mechanical system has its own configuration and because there are no standardized characteristics applicable to all configurations, the dynamic simulation is performed using general rigid multibody equations [5]. In this case, the characteristics are the mechanism's geometric parameters and the masses and inertias of the different moving parts. These parameters can be easily obtained using commonly used CAD software. The following relation between joint accelerations \ddot{q} and forces τ applied on the bodies of the mechanical system is used:

$$\tau = M\ddot{q} + C(q, \dot{q})$$

Where M is the generalized inertia matrix, C is the generalized bias force depending on q - the joint coordinates - and \dot{q} - the joint velocities. This equation can be efficiently computed using Featherstone's algorithm [4].

Interaction with the hydraulic simulation is done in two directions: forward dynamics, where the hydraulics simulation provides forces/torques and the mechanical simulation computes linear/angular accelerations, and inverse dynamics.

The mechanical system can also store energy in the form of kinetic energy when it is moving, gravitation potential energy when the mass are lifted, and elastic potential energy when the spring or other compliant parts are bent.

Power losses proper to the mechanical system are mainly due to friction in the joint motion that can be simplified using coefficients. Taking all these coefficients into account and multiplying them by the corresponding joint velocity modifies the generalized bias force $C(q, \dot{q})$, which becomes a non-conservative force. The actuator force used to fight this friction is

not all used to accelerate the mechanism; therefore the output power is smaller than input power:

$$P_{in} = \tau_{in} \cdot \dot{q}_{in} \geq P_{out} = \tau_{out} \cdot \dot{q}_{out}$$

This approach makes power transfer and efficiency analysis considerably more practical, because the individual parameters are easy to relate to by the designer, as opposed to when considering a generic approach to the complete mechanical system.

3.3.2 Model of Rolling Machine

Another interesting mechanical model to consider is a rolling machine. This system is usually complex to analyze in depth. If the analysis focuses on hydrostatic transmission, the machine can be simplified by a rolling force relationship such as the one developed in [3]:

$$F = W \sin \theta + f_r W \cos \theta + R_a$$

Where W is the load of the rolling machine, θ is the grade of the road, f_r is the rolling coefficient, and R_a is the aerodynamic resistive force.

Once again, even if this is a simplified relationship, it is important to take into account load characteristics in order to enhance simulation analysis.

4. Examples using Automation Studio™

The following examples show that software like Automation Studio™ allow the configuration of complete circuits or targeted functions using components from renowned manufacturers' catalogs. Since product and application engineers have already tested these components and collected significant application information, this expertise and component knowledge can be used to greatly benefit the system designer by storing complete component knowledge in each element. It then becomes possible to interface with the virtual machine, always using realistic conditions, and to maintain optimal performance even when changing the previously selected components or by modifying the initial circuit design.

This Machine Knowledge Management takes the analysis beyond the hydraulic system. It allows including all the related selected and optimized technologies in the system analysis. This provides an

environment where an operator can interface with all aspects of the system providing an educational experience with different operational machine modes and behaviors.

4.1 Open Loop Load Sensing Energy Consumption Analysis

This first example shows a comparison between two different systems based on the same duty cycle. The system represents a simplified version of a lifting and compacting mechanism of a refuse truck. Both circuits are shown in Fig. 4.

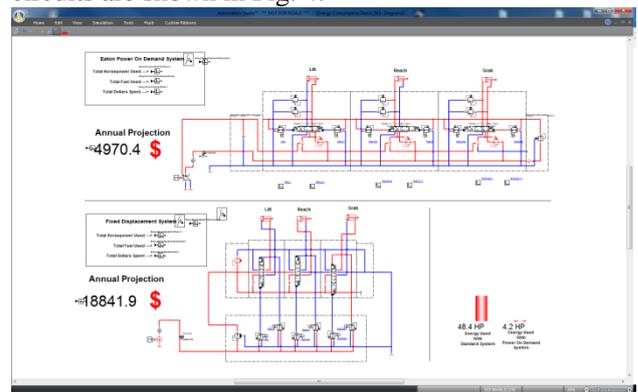


Fig. 4 Open-Loop Comparison

The upper circuit is built using load sensing and load independent valves of the CML60 Series from Eaton. It is compared with a traditional proportional circuit with a fixed displacement pump and proportional valves CM80 series of the same manufacturer.

These proportional components are built in Automation Studio™ using advanced but user-friendly directional valve models containing all the characteristics needed. In Fig. 5, the manufacturer's flow curves are already inserted in the valves used in each circuit.

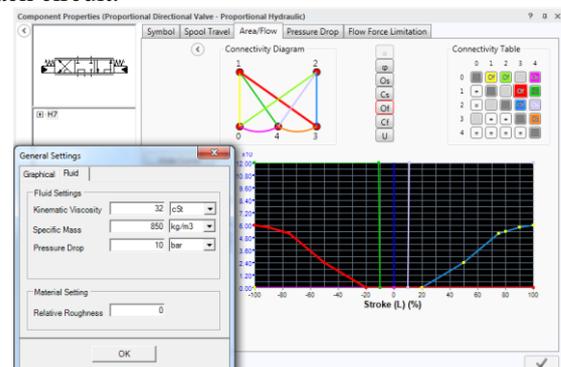


Fig. 5 Valve Model – Flow Characteristics

These curves are defined for a specific pressure differential and flow characteristics, to ensure proper simulation results as described in section 3.2.2.

With these readily available valve flow and pressure drop characteristics, and with the realistic simulation of the pump efficiencies - variable displacement load sensing in the first circuit and fixed displacement in the second - we easily and efficiently highlight the differences in energy consumption in the two previously shown technologies.

If the pump is driven by a diesel motor, we can add an extra level of analysis based on a repetitive or random duty cycle. It becomes possible to annualize the energy consumption of any hydraulic or mechatronic system, which allows us to clearly see when to prioritize the initial cost or the operating cost, and to quantify the environmental impact of the system.

4.2 Hydrostatic Transmission Design & Energy Consumption Analysis

This example is patterned directly on the traditional way of designing and analyzing hydrostatic transmissions. However, it is shown that with the use of Automation Studio™ and catalogs of preconfigured components, the analysis tasks are simplified, because the software performs advanced calculations with these virtual hydrostatic transmissions and then provides a wide range of information useful in the study of energy conversion capabilities of the real power transmission system. This includes conversion range, operating limits, as well as other criteria from a sizing point of view. It also allows performing efficiency analysis of individual components involved in a complete power transmission chain, from the energy source, thermal or electrical, through the hydraulic components, down to the moving load, as explained in section 3.

Fig. 6 shows an example of component efficiency mapping using a 4 dimension curve $\eta_{op} = f(D_p, \Delta p, \omega_i)$ typically used for an axial piston pump that can be fully customized with Automation Studio™. It gives precisely the energy losses, which would have been very difficult or impossible to obtain by building a system of equations as a function of the technology and the geometry of

the pump. Therefore, provided the known efficiencies are available, the pump model is accurately simulated at all the desired operating points. Note that for that analysis the viscosity isn't considered, since it is possible to use a correction factor to take its effect into account and improve the precision of the calculation.

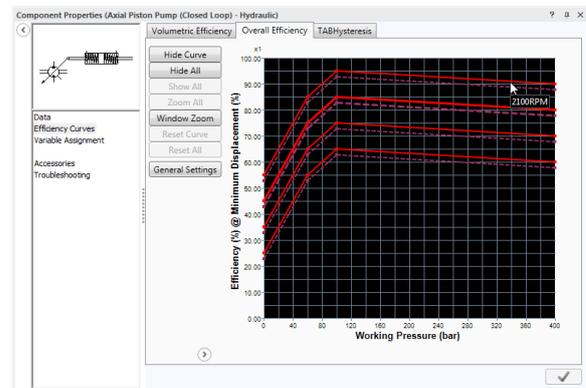


Fig. 6 Overall Efficiency Mapping using 4D curves

Since such curves are available and configurable for other components, it is possible to set the efficiency of each component and study its impact on the overall system efficiency.

As a case study, this example shows a hydrostatic transmission using Linde's Series 02 axial piston components, including a variable displacement HPV pump and a fixed displacement HMF motor. Note that these components are taken directly from the Linde Catalogs, which offer standardized and modular symbols, as well as all the relevant technical data for simulation of a hydrostatic transmission system. They are easily interchangeable to test creative configurations in order to find the best solution according to predefined criteria, like studying the operating limits and other considerations.

Fig. 7 shows the complete system's power balance by visualizing the amount of power transited at each stage of the conversion process.

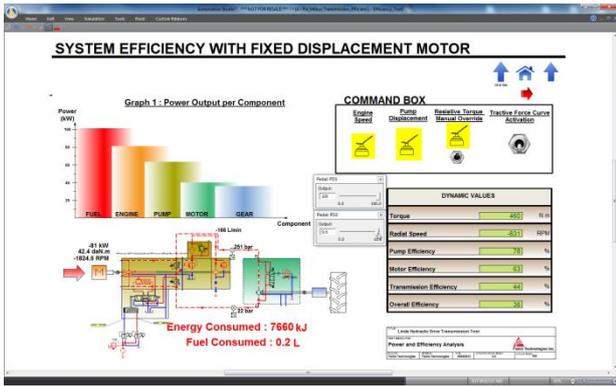


Fig. 7 Closed-Loop System Design/Efficiency Analysis

It is then possible to optimize component selection and the operating modes according to the kind of load the transmission is moving and other application-specific test configurations. These kinds of analyses are particularly interesting with the usage of axial piston products, which efficiency is drastically reduced when operating at small displacements.

5. Conclusions

Downstream design consisting of using preconfigured modules offers many advantages for efficiently developing fully integrated systems. Components can be packed with advanced behaviors and manufacturer-specific data, which frees the system designer to focus on integrating the complete mechatronic system. Also, this modular approach allows for easy reuse of components, which makes system customization more efficient and less costly.

With this approach, it is possible to build complete virtual machines that simulate several technologies and offer a realistic behaviour even in an interactive simulation framework. This allows for improving system analysis and offers new possibilities such as maintenance technician and machine operator training.

Through extensive use of manufacturer catalog components and integrated use of different technological modules, Automation Studio™ empowers the user to design complex mechatronic virtual machines and to accurately simulate them.

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