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Layout and optimising of electric drive for tractors

Within several years of work at the Chair of Agricultural Engineering, TU Dresden a test bench with diesel-electric drive was developed. Presented here are the results of the first working phase, which concentrated on drive layout and development of models for investigating the stationary and dynamic behaviour of the drive. First trials on the dynamic behaviour of the drive train indicated the possibility of realising a new type of drive train control based on application of set torque values.

The influence of electrical drive has affected development tendencies in the car industry. Battery driven, hybrid or fuel cell vehicles need electrical drives that are efficient, small and light. Improved magnetic materials and the steadily growing performance capacity of microprocessors have led to the realisation of new motor concepts with higher efficiency and reduced size. Applying electrical drive to tractors would allow completely new functions for these vehicles. Alongside the realisation of a bi-directional IVT transmission with operator-friendly control interfaces, such tractors could serve as mobile generators for a range of machinery. The application of supplementary electrical energy storage would allow short-term increase in available drive power for vehicles.

A highly-regarded diesel-electric tractor prototype was introduced by Schmetz in 1998. Even 40 years ago Allis-Chalmers developed a fuel cell driven tractor. If the fuel cell establishes itself as an alternative energy source in vehicle production, the system would represent serious competition for the farm tractor diesel engine. Investigations on diesel-electric drive concepts have been conducted since 1996 at the Chair of Agricultural Machinery, TU Dresden. After a phase of theoretical comparison of possible drive configurations, a test bench was constructed for collecting experience of diesel-electric drives through practical trials and for comparison of pure electrical power transfer („serial hybrid") and a power-split drive with regard to their efficiency progression. Additionally, a control for a diesel-electric drive was developed and tested on the bench.

Test bench drive conception

There's a choice when it comes to realising a diesel-electric drive. If one ignores battery drive there are still so-called „serial hybrid" and power-split drives.

Whereas with serial hybrids the total mechanical power delivered by the diesel engine is converted into electrical energy and back again, power-split drives use mechanical and electrical power transfer. The serial hybrid advantage lies in the simple structure and the increased constructive degree of freedom because of the freely-selectable order of the diesel engine/generator unit. Contrary to this, using the power-split reduces the demands on the dimensioning of the electric drive and, at least within a certain working range, leads to increased drive train efficiency. The quantitative difference, and the speed range with the greatest differences to the serial hybrid, depend on the selected transmission configuration and especially on the application of shift transmissions.

Depending on the positioning of the electric drive in the drive train, power-split drive at the input and output coupled structures differ. *Figure 2* shows the principle structures of the drive variants.

The proportion of power transferred the electrical way onto applied draught performance of the power-split drive depends on the speed. *Figure 3* shows the typical curves of the proportion of the electrical power transfer with constant diesel rpm assumed. With the input coupled arrangement there occurs at low speeds a „blind" power flow (recognisable through the negative values of the power share). With output coupled the total power is transferred electrically when starting. This means that total starting torque must be produced by the electric motor.

Both drive configurations have as characteristic parameter the speed at which the electrical drive stands still and total driving power is transferred mechanically. Although

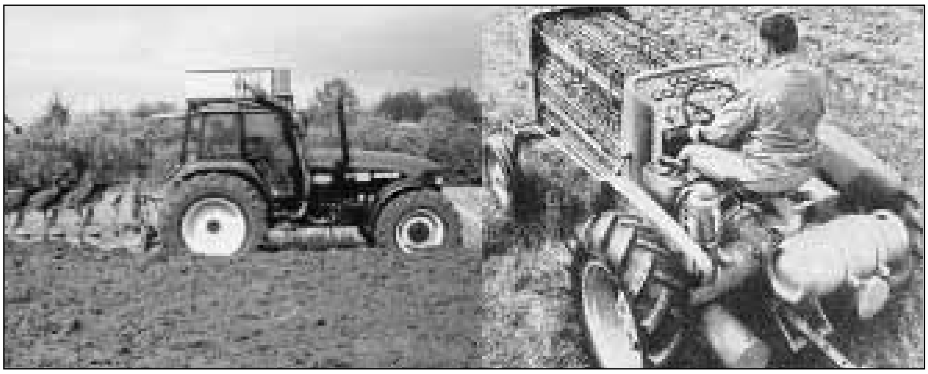

Fig. 1: Diesel-electric tractor by Schmetz and fuel cell tractor by Allis Chalmers

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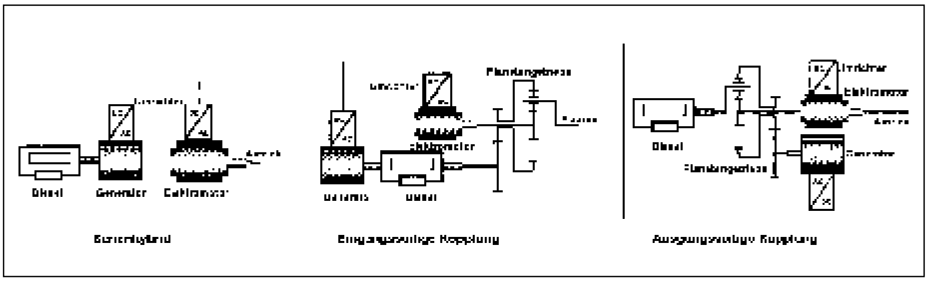

Fig. 2: Serial hybrid and power-split configuration.

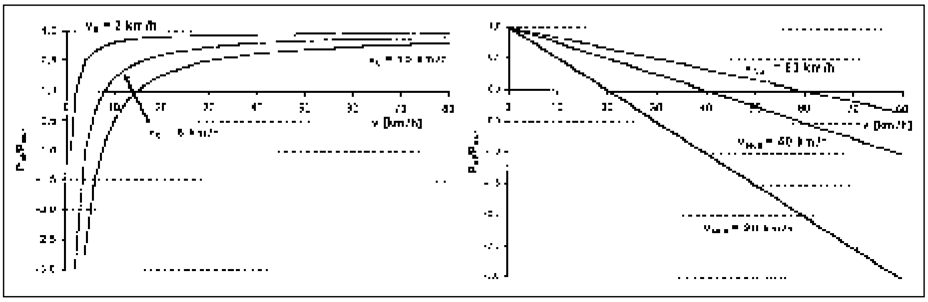

Fig. 3: Electric power share of the power-split configurations (losses not considered) (left: input coupled; right: output coupled)

even at this working point there's a certain loss of power is converted within the electrical drives, a very good drive train efficiency is to be expected at this speed. It is easy to see from figure 3 that the best efficiency value of the input coupled power-split can be expected in the main working range at relatively low speeds whereas the output coupled layout should reach its optimum at higher speeds.

After the analysis of the drive configurations, a test bench for diesel-electric drive trains was designed at the Chair for Agricultural Machinery, TU Dresden. The following targets were aimed for:

- development of a test bench which could be operated in the drive modes „serial hybrid" and „input coupled power- splitting"
- determination of drive component losses and verification of models for the evaluation of power flows within the drive train
- development of a control system for the experimental drive
- implementation of a controller program for operating the test-drive controls

The development of the test bench is shown in *figure 4*.

A tractor „torso" forms the kernel of the test bench with a generator attached instead of a front pto. Because the front pto is removed the generator runs at the same rpm as the diesel engine. The generator converter is linked via two motor converters over an intermediate circuit. The asynchronous motors controlled by these converters both drive the respective sun gear of a planetary transmission. The hollow wheels of the planetary transmission connect with the rear axle of the tractor torso via high ratio gearing. To achieve an as high as possible rpm for the hollow wheels, the end drives for the rear wheels were removed. With a real drive train the rpm of the bridging shaft has to be adjusted to the rpm of the wheels via gearing. However, to minimise size of required load machines on the test bench, high ratio gearing was used between the bridging shaft and load machines.

The transmission layout meant the same asynchronous motors could be applied for the drive motors and the load machines. All were controlled by standard industry converters. Generator and generator converter came from a series developed for urban busses. The generator was able to receive the rated 63 kW power of the diesel engine.

Calculating the efficiency curves

Applying the parameters and characteristic curves of the components on the test bench enabled the calculation of efficiency, fuel consumption and emission values of a „virtual vehicle". This was understood as a tractor with the same electrical machines, converter and diesel engine, but modified transmission components (matching actual wheel revolutions instead of the higher rpm of the diesel engine, use of a simple gearing between diesel motor and planetary transmission instead of the test bench's complex power shift transmission) were applied.

Calculations were by the Matlab program system. Its advantage lay in the simple treatment of matrices and complex numbers as well as the possibility of using the additional Simulink module for dynamic simulation of the system.

Figure 5 shows the calculated progression of the full load drive train efficiency for both observed configurations. The power-split layout, in comparison with the serial hybrid, reached an around 7% higher value of maximum drive train efficiency.

Generally the calculated efficiencies, especially for higher speeds, are not yet satisfactory. The main reason for this are the too high magnetic losses of the asynchronous

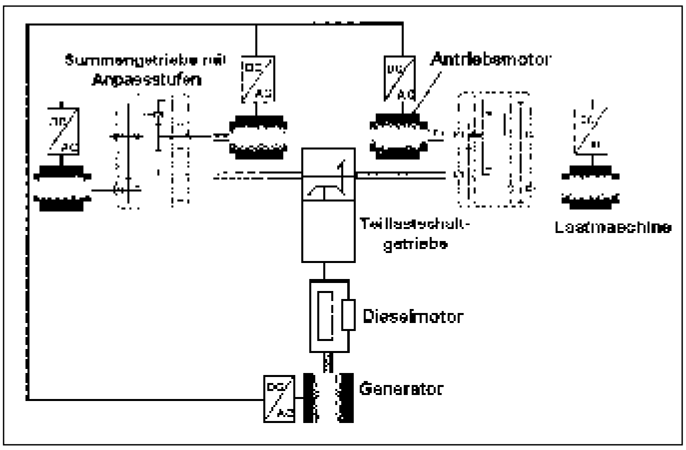

Fig. 4: Test-bench structure

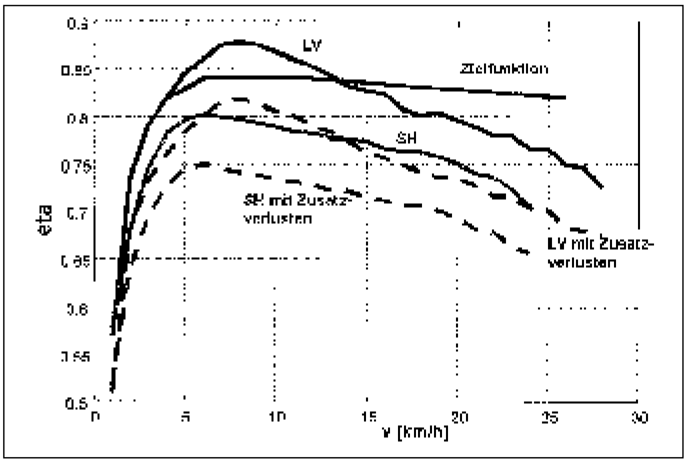

Fig. 5: Calculated full-load efficiency of the „virtual vehicle"

motors. Using higher value (and with that unfortunately more expensive) iron material makes possible a clear increase in efficiency in this area. A second alternative lies in the use of shift transmissions which would substantially reduce the required rpm range of the motors.

Alongside the virtual vehicle, modelling was also based on the drive built on the test bench. The comparison of these calculated values with the measured efficiencies showed a good agreement. With power-split drives a maximum difference of 4% was determined. For the serial hybrid, where the difference between trial drive and „virtual vehicle“ was less, the differences were even less.

Investigations into the dynamics of drive components

For developing a control for the drive train the dynamics of the applied components have to be first determined. *Figure 6* shows the results of the trial for identifying the dynamics of the electrical drive and of the diesel engine including injection governor.

The electric drive followed a set torque value. The rise of the given torque can be adjusted in the set up of the frequency converter. To allow stable working of the drive (without having to switch off through overloading), a value of 1500 nMs was not exceeded. For this, from idling the rated torque of 382 Nm within 0.25 s was adjusted for. The diesel injection governor required a set rpm value. It could be seen that, after a pause of around 100 ms, the given torque of the diesel increased. The full load curve was achieved after a further 250 ms. After reaching set rpm value, the injector governor reduced the required torque.

Evaluating the results, it was clear that the control times of the electric drive were sufficient. Problems occurred through exceeding the torque and through steep rises in electrical motor rpm and this led to an improved software being used for the applied frequency converter at the end of the trial described in this paper.

Regulating the drive train

Usually electrical drive trains, as in the test bench, are driven with a predetermined set torque value. The application of this sort of strategy in a tractor leads to alterations in the entire vehicle control. Currently tractor drives comprise a diesel engine with rpm-restricting governor and transmission with adjustable gear ratios. The wheel revolutions controlled in this way lead, under given wheel-ground relationships, to opposite reactions at the wheels which apply forces via transmission through to the diesel engine. To achieve full exploitation of the available diesel engine power the transmission must be adjusted according to the ground conditions.

A regulating on the basis of desired torque values enables the setting of a desired value of drive train power production. This set value can be reached on the basis of the engine’s rated power and the efficiency of the transmission. With the available information regarding wheel rpm, the power value can be converted into torque values. With this, the expected forces acting on the crankshaft can already be calculated before the rated torque value is transmitted to the frequency converter. Wheel revolutions can then be deduced from the appropriate torque values and the prevailing wheel-ground conditions. Additional algorithms can be integrated into the frequency converter to limit the increase in wheel rpm (reduction of torque when wheelslip occurs).

Figure 7 shows the simplified structures of both regulating strategies. Here, special attention should be given to the case where regulating is carried out on the basis of set rpm where the regulating can only be varied through gearing ratios adjusted with limited dynamics in order to compensate for the influence of the high dynamic altering forces. Contrary to this, where a set value is given for the drive moment, the wheel revolutions have to be monitored because these can only slowly change as an integral parameter.

The regulating based on set drive torque was implemented on the test bench. The system „dSpace“ was used for controlling the complete test bench. This Windows-based system enabled the use of a block diagram built-up within „Matlab/Simulink“ which when automated is translated into a „real time capable“ code for a DSP. Because of this interface to Matlab/Simulink it is possible to investigate the total drive train, its control and predetermined load cycles, in the simulation first of all. When the simulations have led to satisfactory results the models of the drive components can be substituted with the real hardware on the test bench (hardware in the loop). In this stage only the forces acting on the wheels within the simulation models is calculated and transmitted as set torque value to the frequency converters of the load machines.

While the graphic input of a control structure is very easy to operate in Simulink with its simple linear systems, one quickly recognises the limits of this method with more complicated structures. Especially the number of case differences is easier to tackle with a high level language such as „C“ than with block diagram. For this reason the core of the drive control is implemented through the use of the C interface of Simulink.

Figure 8 shows the simplified signal flow plan of the test bench. The application of the driver (draught or braking forces, required rpm of the diesel engine), and information regarding the drive train components are processed by a rated value calculator. When the driver has given a required value for the diesel engine rpm this is not overwritten by the required value calculator. If no required value is given, then the required value calculator (with regard to fuel consumption, emissions or required draught reserve) can calculate an optimised rpm. Input parameters in this calculation are the set wheel rpm and the required value for the drive force. From the comparison of the generator-required load moment on the crankshaft and that from the injection governor adjusted set torque of the engine, the loading of the engine through an-

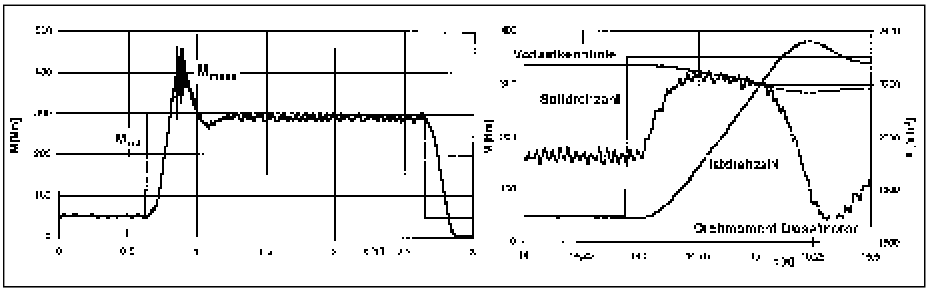

Fig. 6: Identification measurements of the dynamics of electric drive (left) and of diesel engine

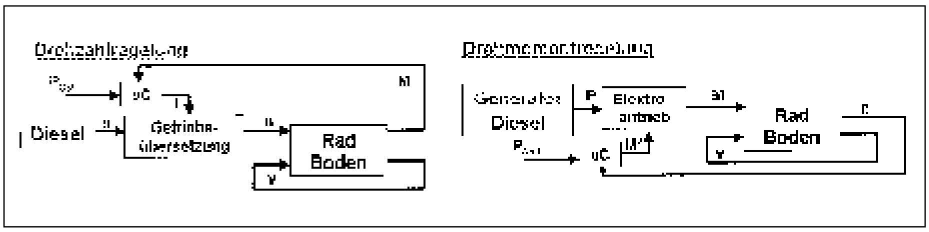

Fig. 7: Comparison of control schemes based on speed or torque commands

cillary uses can be kept separate. The last function could not, however, be implemented on the test bench because the injection governor signal was not exact enough although there are new systems which are claimed to be in the position to offer the required information.

The desired value calculator converts the draught force desired value into a desired torque value and tests whether this value is attainable. There are two grounds why this desired value must be reduced: One, the conversion of a desired torque value at given wheel rpm can lead to a power requirement on the diesel engine which it cannot meet even at maximum revs. In this case, a permanent reduction in the desired torque value should be made. A short-term reduction in the rpm desired value may be needed when an adjustment (increase) of the diesel rpm to the power requirements should take place. Where there's a sudden change in the draught force desired value given by the driver the rpm of the diesel must be increased as rapidly as possible.

The values converted in the desired value calculator follow the idea of the „available crankshaft torque" In order to bring the diesel engine rapidly to the required rpm there must be a sufficiently large difference present between the torque produced by the diesel and the available load moment at the crankshaft. The load forces come from the sum of the generator torque and the torque from the ancillary consumer. Following the reaching of desired rpm the generator torque must not be allowed to exceed the maximum available torque. In order to achieve this requirement the maximum permissible torque of the electrical drive is calculated from the efficiency range of the electrical drive, the generator and the mechanical components. This parameter is used for the limiting of the desired torque value.

The desired value calculator was tested in the simulation and on the test bench through the use of a defined driving cycle. For these tests the rpm of the electrical drive was kept constant by the load machines. The desired value of the diesel rpm was set by the desired value calculator, thus allowing matching of the diesel rpm to the required power.

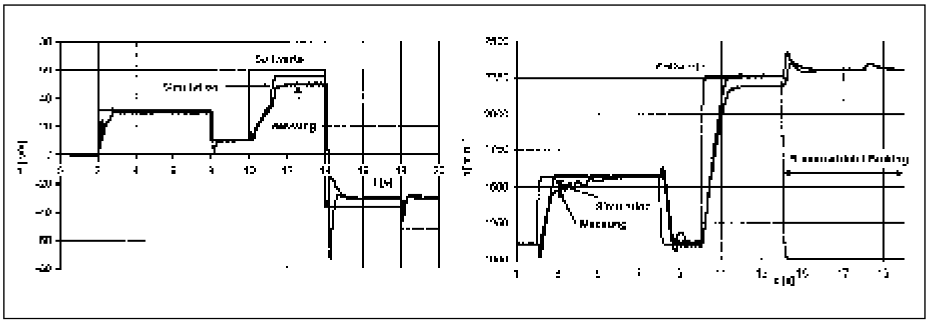

Fig. 9: Simulation and measurement results for wheel power (left) and diesel engine r.p.m.

The results from simulation and measurements are presented in *figure 9*. In the first part (2....14 s) the electrical drive powers the vehicle. A negative desired torque value led to the electrical drive passing into the generator mode.

The curve of the applied draught force followed its desired value with a certain delay in that first the diesel rpm had to be increased. The desired value which was reached again after 10 s cannot be applied because it would lead to an overloading of the diesel engine. Following the change into braking action, the rpm of the diesel is monitored by the desired value calculator. The required rpm of the diesel is set at idling value so that the fuel injection amount stands at nil. The restored electrical drive power is limited to a value which does not lead to exceeding of the maximum permitted diesel rpm.

The greatest differences between the simulated and the recorded curve progress appeared in the areas where the given torque of the electrical drive changed. The difference can be explained through the relatively simple model of the electric drive (PT1 behaviour). A highly dynamic field-oriented control of the electrical drive, which is state of the art with realised traction drives, reflected the simulation model utilised better than the regulating of the built-in frequency converter used on the test bench.

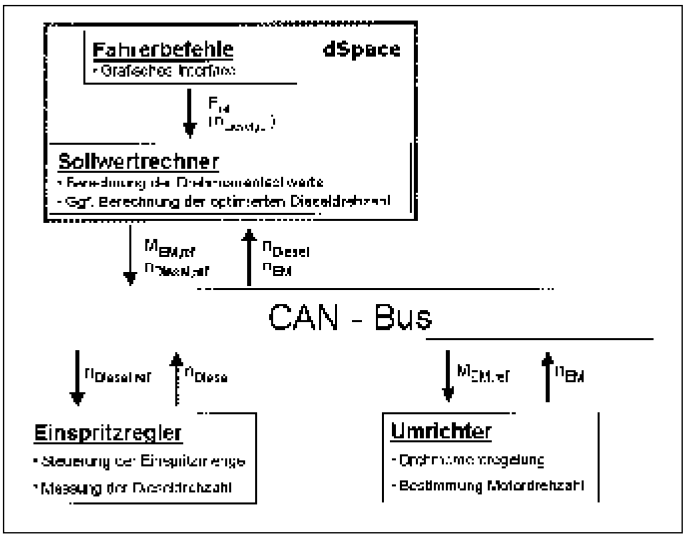

Fig. 8: Simplified control scheme of the drive train at the test-bench

Further, in particular in the area of maximum power application, there are longer lasting differences between the simulated and recorded values to be seen. Possible reasons for this are the differences between the actual efficiency of the electrical drive and that in the efficiency degree ranges used in the simulation. Especially the temperature-dependent rolling resistance of the asynchronous machines came in question as error sources. Further reasons could lie in the analogue signal transmission of the desired values for the frequency converter and the non-linear reaction of the injection governor.

Despite the mentioned limitations, the tests demonstrated the functionality of the implemented algorithms. For further development of regulating it would appear sensible to evaluate the generator-applied torque (generator converter signal) and diesel motor characterised torque. The difference between both parameters gives a measurement for the requirements of the ancillary consumer. Further, from the information on the generator torque the real efficiency degree of the electrical drive can be determined and thus the applied efficiency degree range corrected.

Summary and outlook

The investigations into diesel-electric drive trains which took place within the Chair of Agricultural Machinery, TU Dresden took place on a test bench verified model for stationary and dynamic behaviour. Application of power-split meant efficiency improvements of up to 7% being determined for the observed drive configurations. In order to fulfil the practical requirements regarding degree of efficiency curve on a tractor drive train the loss of electrical drive power at higher rpm must be reduced vis-a-vis the trial drive.

Using diesel-electric drive allows new structures for drive control. First tests show that the functionality of an algorithm based on the giving of desired values for torque. Further investigations and the evaluation of additional signals will follow. In the long term these should lead to the construction of a drivable prototype.

In the long term only the costs involved will decide on the introduction of diesel-electric drive trains in tractors. There is no doubt about the technical practicability and related additional functionality

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