The Eindhoven experimental electric vehicle : vehicle design and drive train

determined at C_5 rate. The experimental C_R was found to be 31 ± 5 Ah, while the calculated C_R was 19.2 Ah.
Fig. 10 shows the cell voltage (E_D) at the highest discharge peak and the cell voltage (E_C) at the highest charge current peak during 13 cycles and the cell voltage E_R at $I = 0$ at the end of each cycle. In the figure the computed data are given from 8th to 13th cycle.

5. CONCLUSIONS

The effect of state of charge of a battery upon the current voltage characteristics was described by a simple relation. Calculation of the state of charge during duty cycle discharge was found to agree within 7% with experimental results and the actual battery voltage during electric vehicle operation agrees with the simulated performance.
With this model matching of power train and battery can be evaluated (9) and energy use and operation range can be predicted.

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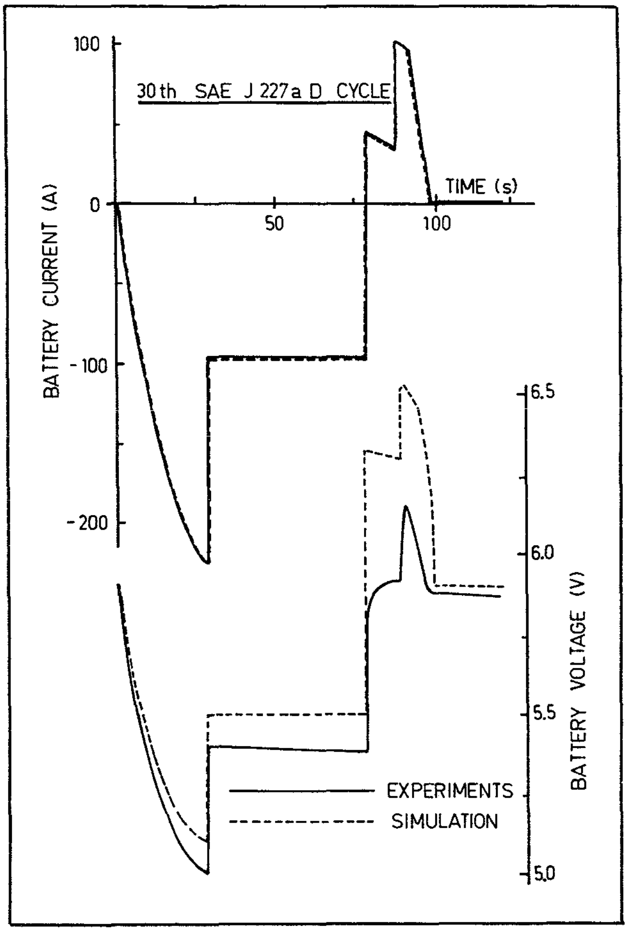

Fig. 9 Simulated and experimental battery voltage and current profile during 30th SAE J 227 aD cycle

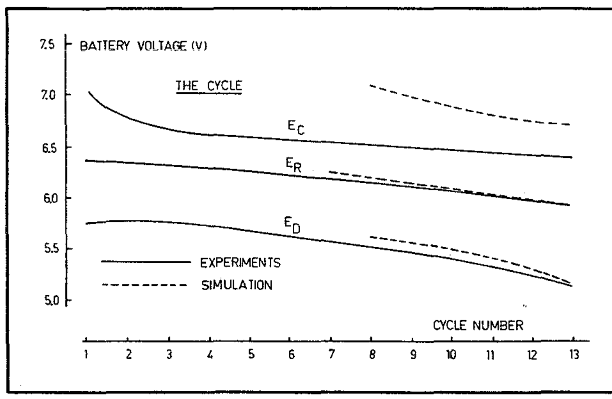

Fig. 10 Change in battery voltage at highest discharge current peak (E_D), at highest charge current peak (E_C) during 13 consecutive THE cycles and battery voltage at the end of each cycle (E_R)

The Eindhoven Experimental Electric Vehicle: Vehicle Design and Drive Train [1])

SUMMARY

At Eindhoven University of Technology a multidisciplinary team of chemical, electrical and mechanical engineers is collaborating on construction of an electric commuter car/van.
A VW-Golf which concept appears to be very suitable for this purpose, has been electrified. Car-body and rear suspension were modified thus that a rapidly exchangeable battery pack could be placed in a central box.
Various ways of controlling the powerflow from the 16/33 kW Siemens dc-motor to the wheels will be tested in this vehicle.
Three systems, which are under construction, are described:
- **battery switching, field weakening and a fixed ratio transmission**
- **battery switching, field weakening and automatic gear-shifting**
- **fully electronic control by means of choppers.**

by L. A. M. van Dongen and R. van der Graaf [2])

1. Introduction

During the last decade the importance of the development of electric road vehicles has widely been recognized. In the beginning much effort has been displayed on the construction of electrically driven buses and vans for a variety of reasons.

A group of interested persons at the Eindhoven University of Technology discerned the challenge which was put in this field by the passenger car as a replenishment of those activities. Especially in this application some features of the electric drive, such as battery weight, energy-efficiency of the drive line, selection and construction of components to be

[1]) Paper gepresenteerd tijdens 'Drive Electric 1982' te Amsterdam

[2]) Eindhoven University of Technology, Eindhoven, The Netherlands.

used, cost of these components, vehicle safety aspects, asked for a thorough investigation.
Optimization of a vehicle concept with respect to these features was considered necessary, and therefore a multi-disciplinary team was formed in which the chairs of Electrochemistry (Department of Chemical Engineering), Electromechanics (Department of Electrotechnical Engineering) and Transport Research (Department of Mechanical Engineering) are taking part.

On-the-road testing of various methods of motor control and types of battery would be an important part of the investigations.
It was expected that the project would give rise to a number of educationally very interesting studies for the final theses of postgraduate students, whereas the members of the multi-disciplinary working group hoped to learn a lot from each other.
These expectations are largely being fulfilled.

2. Vehicle Concept

Specifications:
In an early stage the vehicle specifications of the Eindhoven Electric Vehicle (EEV) were set up:

- Top speed: 80 km/h
- Acceleration: 1.5 m/s^2 up to at least 50 km/h
- Operating range: 100 km
- Passenger capacity: 2 + 2 (two adults with two children or luggage)
- Rapidly exchangeable battery pack
- Distinct attention should be paid to the active (road-holding and vehicle handling characteristics) and passive safety (mechanical and electrical in the case of collision).

From these specifications the purpose of full compatibility of the EEV with normal urban and suburban traffic can be noticed. It will also be clear that the operational demands of this electric passenger car are strongly determined by the availability of electrochemical batteries. In fact the lead-acid battery still appears to be the only short term alternative for the independently moving road vehicle.
The restricted energy and power density and the excessive weight of this energy storage system are responsible for the limited speed, acceleration and operating range. For purposes of range extension and improvement of the battery service-ability it was decided to install a rapidly exchangeable battery pack in the vehicle.

Technical concept:
To obtain a reasonable range the battery weight will amount to about one third of the gross vehicle weight. The car will show proper steering characteristics if this large proportion of mass has a low centre of gravity with a good weight distribution over front and rear wheels and a moment of inertia that is as low as possible with respect to the vertical axis through the car's centre of gravity.
Hence it can be concluded that the batteries should be placed near the middle of the car.
Crash safety will also be favoured in this case, as the batteries and connectors are situated away from the outskirts of the vehicle.
These considerations, together with the required quick exchangeability of the battery pack, led to the concept of a central battery case in the floor of the car body. By integrating this case in the body a kind of backbone is created resulting in good structural strength and stiffness of the total construction.
This concept of a central battery case also facilitates meeting the already early discerned need for conditioning of the batteries [1].
This conditioning comprises:
- ventilating the battery compartment to remove the escaped hydrogen gas
- heating the batteries during winter time; in order to prevent dropping of the capacity to too low a level, the temperature should be kept above 15°C
- cooling the batteries when the temperature would reach too high a level; above about 50°C the active mass can deteriorate.

Selection and modification of a car:
After some preliminary design studies [2] it was decided to start from an existing passenger car or light van which would be modified in order to meet the requirements mentioned before. Thus a great deal of body engineering is avoided and the development efforts can be concentrated on propulsion systems and chassis modification on behalf of the battery pack.
In selecting a car the following criteria were applied:
- the car must have front wheel drive so that the voluminous battery case can readily be accomodated
- the rear wheel suspension should permit accomodating this case without drastic modification of this suspension
- the car should be able to carry the extra battery weight of some 5000 N with only minor changes; this implies that the gross vehicle weight will be at least 15000 N.
- sufficient room should be available between the front doors to accomodate the battery case and two seats
- the motor compartment should be able to house the different types of drive systems (see 3) that are to be tested.

It appeared that out of the small European cars the Volkswagen Golf fulfilled these requirements in the best way. Thus the EEV has been built upon this type.
With type and weight of the vehicle known, the power requirements of the drive train can be stated. To maintain the fully loaded vehicle at its required top speed of 80 km/h, the propulsion motor should have a continuous power output of at least 13 kW. Among the available electric motors the Siemens 1GV1, being a separately excited motor, especially developed for electric vehicles, fitted best into the specifications with:

- nominal power 17 kW
- maximum power 34 kW
- nominal speed 2200 rpm
- maximum speed 6700 rpm
- nominal voltage 130 V

With this motor the estimated acceleration of 1.5 m/s^2 can only de maintained until approximately 43 km/h; at higher velocities this value will gradually fall down.

In **Fig. 1** the top view of the changed car shows clearly the drive train, central battery case and modified rear axle.
According to the aim of testing various types of battery, the case has been constructed in such a way that batteries with different dimensions can be accomodated.
The batteries are placed in a wheeled sledge which can roll in the case and which is provided with sliding contacts at its front side.

The specifications of the first battery pack to be used, are:

type: Varta 240-15, EV battery
voltage: 20 x 6 V
capacity: 180 Ah at 5 h discharge

Maintenance of the original rear wheel suspension, trailing arms with an integral transversal anti-roll bar, would result in too high a battery pack location.
This construction has therefore been replaced by totally independent wheel suspension with newly constructed inner supports for the trailing arms.

3. **Drive system and motor controller**

General description:
Many passenger car manufacturers are developing and testing several drive systems in various electric vehicles. Due to different vehicle characteristics and testing conditions it is almost impossible to obtain a reliable comparison of these drive trains. Moreover, the near-term objective arises of optimizing drive systems using currently available components with respect to operating rang and primary energy consumption. For these reasons in the Eindhoven Electric Vehicle various drive systems are being constructed and tested under identical conditions.

The dc-series motor has long been regarded as an excellent choice for traction application because of its capability to deliver a large torque at low speeds. Control of the torque generated by the motor can be achieved by varying the magnitude of the supply voltage. A separately excited dc-motor, which provides the best combination of efficiency, performance and controlability for the near-term electric vehicle, is significantly different and has been chosen for the EEV. The speed of this motor can be controlled by field weakening in the speed range above nominal speed and by varying the armature voltage or circuit resistance in the speed range below nominal speed.
As a rule the motor is coupled to the propeller shaft by means of a step-down gear and the motor must therefore be capable of being adjusted over the entire speed range. Simulation studies, however, [3] demonstrate that from an energetical point of view a propulsion train using a variable transmission ratio has to be preferred to a drive system with a fixed gear ratio.

Fig. 2 Interior of the modified Golf, showing the battery case construction

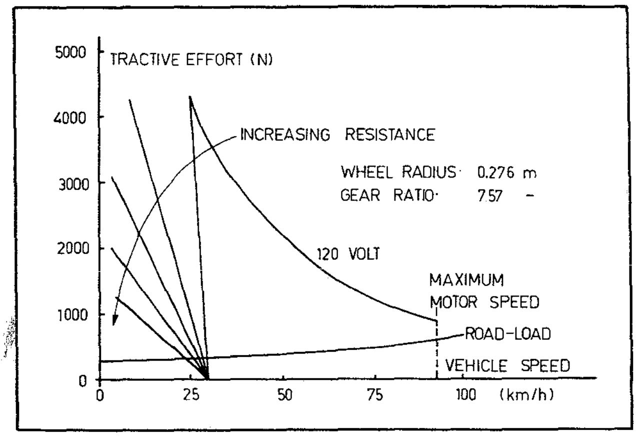

Fig. 3 Resistive motor control

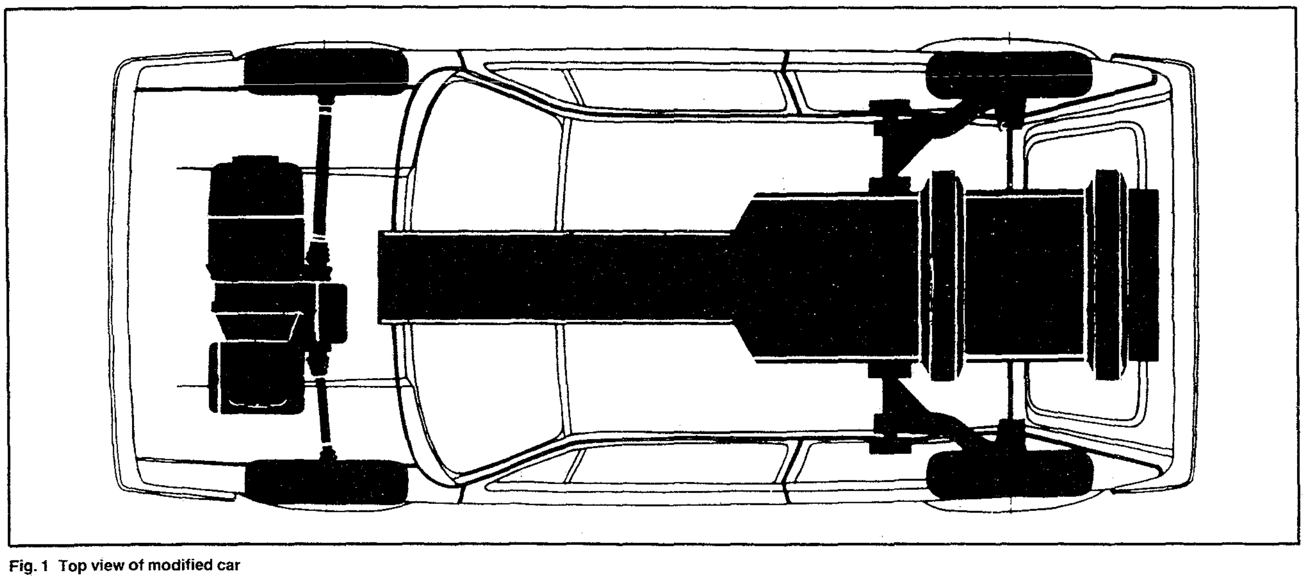

Fig. 1 Top view of modified car

In general, three areas of control can be discerned over the motor speed range:

1. **field weakening** in the upper part of the range.
As the field requires relatively low currents (up to 7 Amps approximately), field controllers are almost exclusively of the cheap single quadrant transistor-type.

As only a limited control range is realized by field weakening, further adjustment is necessary:

2. **adjustment of motor speed** can be performed in various ways:

- Continuously Variable Transmission - Automatic gearbox - Manually shifted gearbox - Hydrostatic transmission	motor control only by field weakening
- Battery voltage switching	
- Armature current chopper (transistor or thyristor)	

The fourth and sixth type permit adjustment from zero vehicle speed. The other types necessarily need:

3. **slipping devices** for starting from standstill
This function can be fulfilled by:
- resistive motor control
- friction type of coupling
- hydraulic coupling
- torque converter

In a preliminary study the control devices mentioned under points 2 and 3 have been reviewed and compared. The various possibilities have to be judged from different points of view, each of them delivering a number of criteria:

point of view	*criteria*	
economical	cost energy efficiency	
operational	reliability maintenance duration of life	
vehicle handling	ease of operating smoothness	
design	feasibility of optimal control feasibility of recuperative braking	
	weight dimensions divisibility	of devices
environmental	noise	

From these considerations it appeared to be desirable to construct and test three drive/control systems in the vehicle:
- voltage switching, field weakening and a fixed ratio transmission
- voltage switching, field weakening and automatic gear shifting
- fully electronic control by means of choppers.

In the first and second system also resistive control has to be comprised for low speeds.
In the following part the selected control systems will by described in more detail.

Resistive motor control
In the past this control has been the most popular type in use because of its low cost and quiet and smooth operation. At high vehicle speeds the field chopper is responsible for motor control and at low speeds resistors are switched into the armature circuit, as shown in **Fig. 3.** In order to provide a smooth operation a sufficient number of resistance steps is required. In the resistors, however, energy destined for propulsion is lost, and regenerative braking is impossible over this motor speed range. This greatly reduces the operating range in the typical type of driving of an electric vehicle: start and stop urban travel. The total amount of energy, which is lost in the resistors, can in fact be reduced by using a multi-speed gearbox, which allows the resistor to be switched out of circuit over a larger vehicle speed range. Because of the considerable energy losses in the resistors, purely resistive control does not deserve consideration for a modern electric vehicle.

Voltage switching
Another apparently simple form of speed control for an electric vehicle consists of a group of electric contacts in combination with some resistance elements. The battery pack is provided with several taps, at various voltages and the contacts reconnect the motor armature to various parallel and series combinations in order to give the appropriate motor voltage depending on desired speed. It is difficult to realize more than three or four acceleration steps, because the number of switching elements almost doubles with each step. Moreover, practical mechanical controllers are often extremely complex due to circuit demands, that are important for reasons of safety, and additional switching devices installed to ensure that all batteries are discharged uniformly.
An automatic voltage switching system has been designed, so that 30, 60 or 120 Volt is obtained at the motor terminals [4]. **Fig. 4** shows that the speed range ratio, that can be controlled by field weakening as stated above, has been quadrupled by simply changing the batteries from series to parallel connections. Only additional measures are required for bridging the start-up range. Although the system just described does provide control of speed, a complete covering of the tractive effort/speed range cannot be realized. Moreover, the tractive effort falls off, because voltage switching occurs at no-load conditions in order to prevent arcing of the switches.
In order to limit the armature current at low vehicle speeds a resistor can be used. This can also be realized in a simple way by using a hydrodynamic torque converter.
Although the damping characteristics of a torque converter

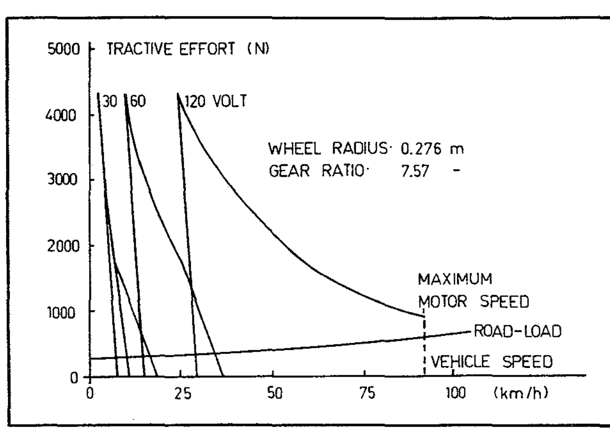

Fig. 4 Voltage switching

are attractive, it has tremendous energetical disadvantages [5]:

- torque converters have high losses in the converting range and a minimum slip of at least 2% occurs in the coupling range
- a torque converter requires an oil pump, the losses of which are high and proportional to the rotational speed.

For this reason a drive train having a fixed gear ratio of 7.57 and the dc motor controlled by a voltage switching system with a starting resistor is being tested in the vehicle now.
By mounting a multi-speed gearbox the number of unattainable operating points in the tractive effort-speed plane can considerably be reduced. The transmission ratios have to be matched in order that:

- as many as possible operating points can be adjusted
- an as high as possible average motor efficiency is realized
- gear changes and frequent speed variations in town traffic do not coincide.

In order to have an impression of the vehicle operating conditions in town traffic several driving cycles have been recorded in typical Dutch cities as The Hague and Delft. After analysis of these recordings and conversion of the results, curves of constant operating time have been constructed in the force-speed plane of the electric vehicle, as is indicated in **Fig. 5** [6].
For convenience of handling during city driving a standard automatic gearbox has been modified. In order to minimize the power losses in the gearbox, the torque converter has been replaced by a primary gear wheel reduction and the oil pump power has been optimized by using a separate constant speed oil pump instead of the standard oil pump. **Fig. 6** shows that the gear ratio of the primary reduction has been selected in such a way that gear changes only occur at less frequent operating points. The individual overall gear ratios stand at 16.58, 9.41 and 6.50 for the first, second and third gear respectively. Since the motor operates at speeds between 2200 abd 5500 rpm and the resistor is only switched in when the vehicle accelerates from standstill, high efficiency and sufficient operating range can be attained by this approach.
Due to motor synchronization during shifting procedures the operational comfort of the drive system is expected to be at least comparable with that of vehicles with an internal combustion engine and an automatic gearbox.

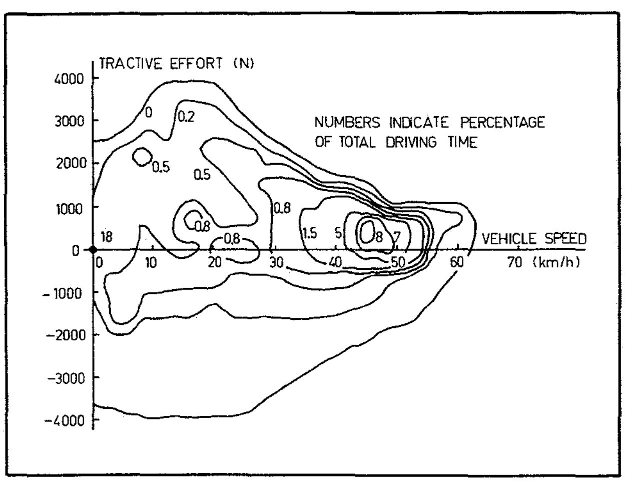

Fig. 5 Vehicle operating points

Fully electronic motor control
Another possible approach is to use an electronic switch in the armature circuit. The switching element is turned on and off at a certain frequency and thus has the effect of chopping the battery voltage.
In this way the armature voltage can be varied smoothly from 0 Volt to the full battery voltage by controlling the time intervals during which the switch is open. The chopper may roughly be regarded as a dc transformer. Since the losses in the chopper stand at about 4% of the power transmitted, the motor power nearly equals the power supplied by the battery. Without much extra expense these choppers allow regenerative braking in the entire speed range.
In principle it is possible to dispense with a multi-speed gearbox when a drive system with a dc motor and a dc chopper is used on the condition that the motor has been designed to handle the high currents drawn during the starting phase **(Fig. 7)**.

Due to the infinitely variable adjustment of the propulsion power a smooth speed control is realized. When the vehicle is moving at low speeds the field current stands at its maximum and speed is adjusted by varying the armature voltage with the chopper. At vehicle speeds requiring motor speeds higher than its nominal speed, the armature chopper applies

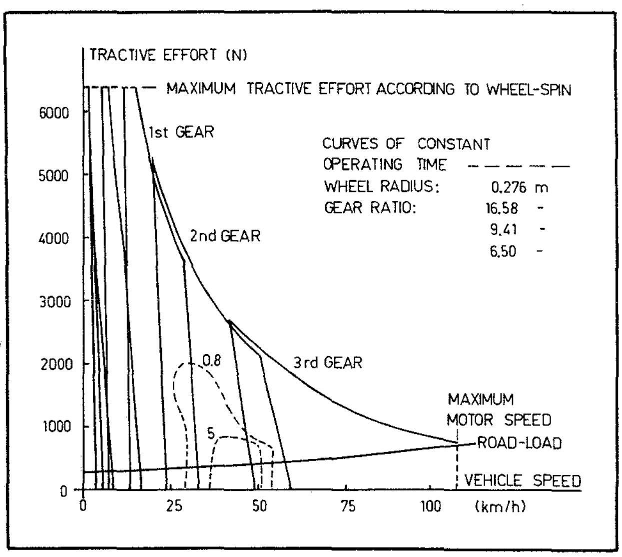

Fig. 6 Voltage switching and a multi-speed gearbox

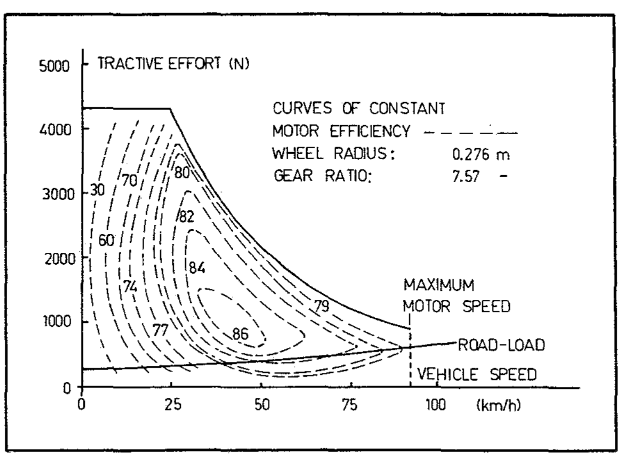

Fig. 7 Fully electronic motor control

full battery voltage to the motor terminals and the vehicle speed can be controlled by variation of the field current.
Yet the use of a multi-speed gearbox has the following advantages (**Fig. 8**):

- during the starting phase a higher gear ratio can be engaged, which reduces the initial current drawn from the battery
- with the possibility of selecting different gear ratios it is easier to meet demands for hill climbing
- since separately excited dc motors are less efficient at low rotational speeds, variable gear ratios allow highly efficient motor operation.

A thyristor chopper for the armature circuit is being developed which will control the Siemens motor coupled to either the step-down gear or the automatic gearbox.
The efficiency of these approaches appears to be high, since the losses in the motor controller are small and regenerative braking is possible. Other advantages are operational comfort and acceptable range. A disadvantage of these drive systems is the costly armature controller, which must be able to handle currents up to the 350 Ampere.

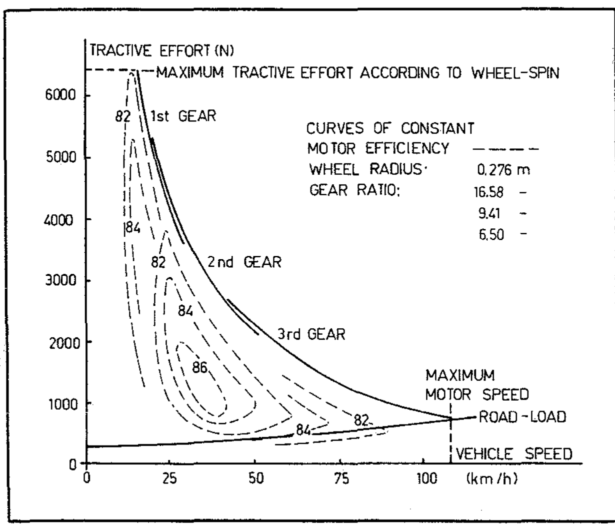

Fig. 8 Fully electronic motor control and a multi-speed gearbox

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Torque control of a shunt wound DC motor of an electric vehicle by means of continuous field control and stepwise adjustment of the armature voltage [1])

ABSTRACT

It is shown that notching armature voltage and continuous field control can be a compromise solution for EV-drives. For the given vehicle parameters the necessarily series resistors are determined. An analysis of field control at different armature voltages is given for both stationary and dynamic conditions. Flow chart and block diagram of the control system are given. Attention is paid to the MOSFET-implemented field controllers and to the measurement of the electromagnetic torque using armature and field current.

by H. C. J. Zeegers [2])

1. Introduction

In the early seventies a group at the university of Eindhoven started to work on the subject of electrically driven vehicles in order to provide authorities with reliable data in this field. In 1973 it was decided to develop an electric passenger car.

1.1. The EV of the Eindhoven University of Technology

The vehicle should meet the following requirements [7]:

1. capacity: 2 adults + 2 children (so called 2+2 car);
2. range: 100 km;
3. topspeed: approx. 90 km/h;
4. cruising speed: 50-70 km/h;
5. acceleration: 1.5 m/S^2 up till 50 km/h;
6. gradients: 20% at stall condition;
7. rapidly exchangeable battery pack;
8. active safety (good road-holding, handling and suspension);
9. good passive safety considering the presence of the battery pack;
10. the electric drive should be such that it offers high efficiency and makes the car easy and pleasant to drive, also for persons used to cars with internal combustion engine. Besides that it should be cheap and servicing should be easy to be carried out by garage personnel with little extra training;
11. regenerative breaking.

After research by the groups transport research [3], [4] and electrochemistry [4], [10], it was decided to modify a VW-Rabbit car and equip it with a 120 V - 240 Ah lead-acid battery. The battery pack is made up of twenty 6 V-batteries. This concept resulted in a total vehicle weight of approximately 1500 kg.
Taking into consideration the requirements for the electrical drive (see point 10), it was concluded that while an armature-chopper has the advantage of easy control and good effi-

[1]) Paper gepresenteerd tijdens 'Drive Electric 1982' te Amsterdam

[2]) Eindhoven University of Technology, Eindhoven, The Netherlands.