NON-CONVENTIONAL SUPPLY OF VARIABLE SPEED DRIVES

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Abstract

Since legislative authorities in the USA demand for electrical automobiles, an increasing interest in electrical zero emission vehicles can be stated. Therefore, reinforced research on adapted drive systems and batteries for the supply are continued, starting from experiences from the past decades. We already started with activities to contribute to the various discussions in this field. In this paper, the methodology and the way of development of an electromagnetic variable speed drive system supplied by fuel cells is discussed. Starting with the properties of a single fuel cell up to a system concept for the electromagnetic energy converter, different possibilities to design a modular drive system are given in a technological discussion. As an application for this system concept an urban mini-bus is discussed. Due to the modular concept, the requirements for the power range of a medium sized delivery van can be reached.

1. Introduction

Fuel cells offer the opportunity to produce electrical as required instantaneously. During operation, they generate the energy without polluting the environment, making them convenient for a hybrid zero emission traction line. Compared to the various types of liquid and dry batteries, this means an advantage for a more safe operation. Generating energy with a fuel cell can be seen as a reverse electrolyse process. To fulfil the required electrical parameters of an electrical drive system, multiple cells have to be combined in order to form the supply module. As energy buffer, a traction battery is included to the drive concept to deliver the energy needed during peak load operation. The ability to recharge the traction battery during brake operation is foreseen. Safety aspects, as well as topics like comfort, are discussed and possible concepts to assess them are proposed. A modular drive technology is derived to have the opportunity to increase the installed power in the drive required by different applications.

The main parts of the drive train, providing 10 kW rated power and 20 kW at peak operation per module, are a fuel cell as permanent energy source, a traction battery as energy buffer and a permanent magnet excited synchronous motor.

2. Drive requirements

For each application, the mechanical system to be driven has a specific set of desired criteria for torque and speed. For the designing the motor drive train, the load conditions, the overall mass of the vehicle and the energy supply used are imported. The force F is given by the summation of the individual forces

$$F = F_{fr} + F_{air} + F_{ac} + F_{sl} \quad . \qquad (1)$$

Where F_{fr} stands for the resistance caused by friction, F_{air} the air resistance, F_{ac} the acceleration force and F_{sl} the force for driving up a slope.

A high accelerating torque is recommended at start and a lower torque is necessary while maximum speed of the vehicle. The typical traction drive characteristics can be in fig. 1. Rapid acceleration at low speed is desired and, in addition, operation is desired at speeds above the base speed n_r and at constant power

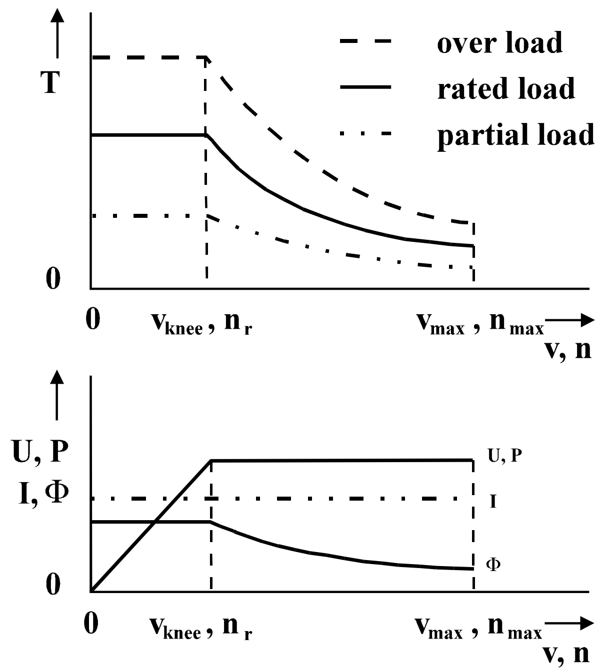

Fig. 1 Typically torque/speed characteristic for traction drives

Table 1 Different transport and delivery systems

Vehicle system	Total weight	Maximum velocity	Acceleration time for 0-30 km/h	Maximum slope
	t	km/h	s	%
Tourist bus	4.0	50	20	15
City taxi	2.5	70	8	25
Mail delivery	2.5	70	8	25
Customer delivery	3.5	50	20	20

up to a maximum value.

Starting operation is performed with increasing power up to the rated value e.g. rated current and full flux in the machine. Operation at values above the rated speed n_r are obtained by flux weakening e.g. constant power, current and supplied voltage. Particular attention during the design and dimensioning of the traction motor must be paid to a high efficiency at rated speed range and at partial load as well. For a high-performance drive such as in an electrical vehicle, a maximum short term torque is to be maintained for acceleration and deceleration during electrical braking operation. The duration of these peak operations has to be defined and checked carefully, taking the temperature of the motor and the power semiconductors into consideration.

As the aim is the development of a vehicle which can be used in public transportation as well as in different delivery systems, table 1 gives estimated values for the different applications.

A tourist bus should be able to transport up to fifteen persons through a town slowly, but with a maximum of comfort. The city taxi has to carry six people within a city, being able to follow the normal traffic flow. The delivery systems can be split into two groups. The mail delivery prefers the normal speed of the city traffic, whereas for the customer delivery the transport capacity is more important.
All these systems have in common that they are running continuously during the whole day, so that there is no time for long charging operations as required in battery energy vehicles.

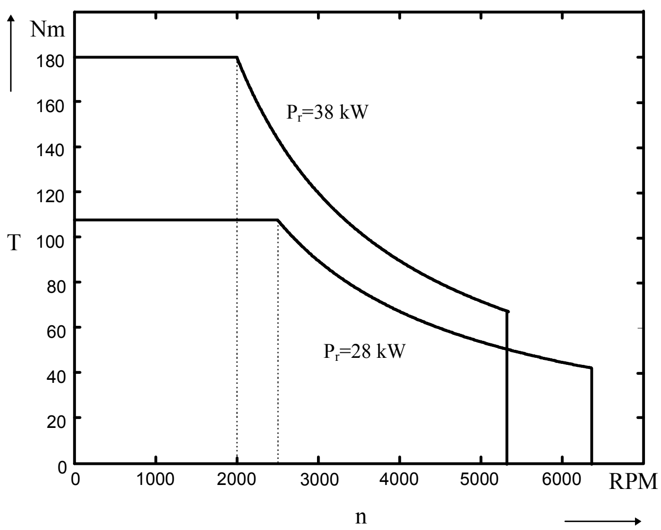

Fig. 2 Required torque/speed characteristics for 3.5 t / 4 t vehicles and for 2.5 t vehicles

Using eq. (1) the definition of the different transport and delivery systems leadings requirements of the traction line. The resulting shape of the torque/speed characteristic is described by the forces required at different velocities and in various situations as shown in fig. 2. The torque/speed characteristics shows that two different systems are necessary to serve all the requirements collected within table 1.

However, it is the aim to develop both traction lines in parallel and to obtain this by modular systems in order to limit the development costs and to obtain a flexible concept. For the vehicles with a weight of 3.5 t up to 4 t, four single wheel drives with 10 kW rated power each are necessary, whereas for the vehicles with a weight of 2.5 t two single wheel drives, each with 15 kW rated power, are assigned.

Emphasis is given to the concept of a 10 kW rated power traction line per module operation on a base speed of 2000 RPM and a maximum speed of 5340 RPM. The peak power is limited to 20 kW for a maximum time of three minutes.

3. Fuel cell and power supply

In this section, the functional behaviour of the fuel cell is explained briefly to allow a look to the specific operation of this novel possibility of power supply and its peculiarities in combination with a variable speed drive applied to an electric driven transportation system.

Fuel cells are emission free and silent energy generating systems with a high efficiency, approximately 36%. The chemical process inside a fuel cell can be interpreted as an inverse electrolysis. Hydrogen is oxidizing and oxygen is reducing, while stimulating an ion transport [2]. Different types of fuel cell systems are developed all over the world. It is foreseen to use an alkaline fuel cell (AFC), because it operates in contrast to other systems available at an acceptable temperature for the traction drive application of approximately 70º C.

Using KOH as electrolyte, the two chemical reactions operating at the platinum electrodes of an AFC are:

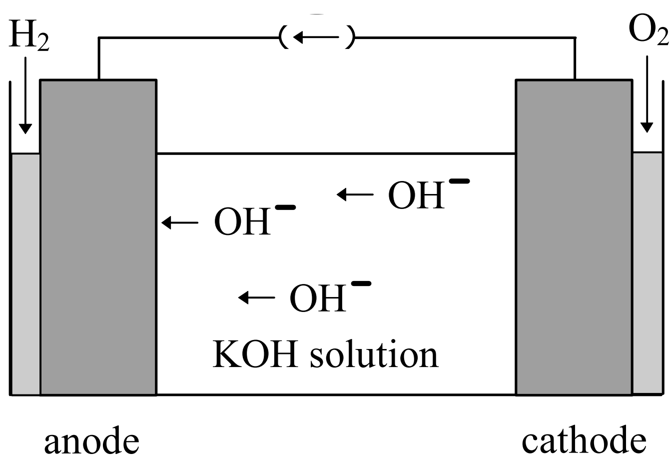

Fig. 3 Principle of an alkaline fuel cell

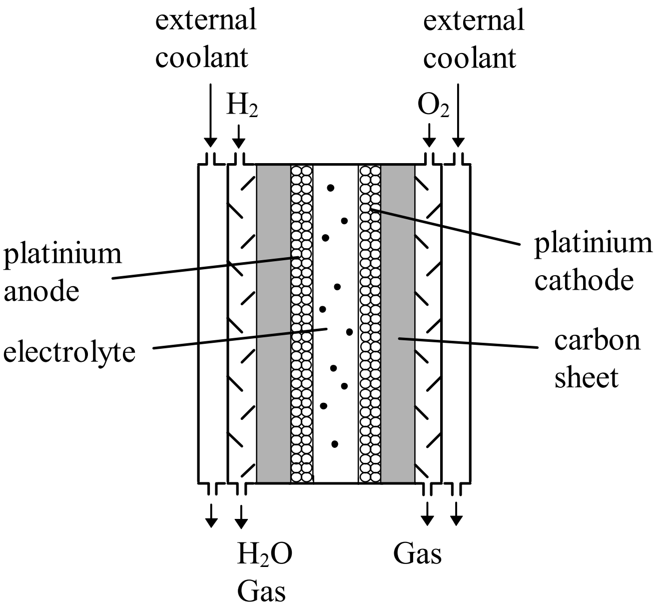

Fig. 4 Detailed cross section view of a fuel cell

$$\text{anode} \quad H_2 + OH^- \rightarrow H_2O + 2e^- \qquad (2a)$$

$$\text{cathode} \quad O_2 + 2H_2O + 4e^- \rightarrow 2OH^- \qquad (2b)$$

The ions are transported by the electrolyte and the electrons are moving via an external circuit giving the electric current. Fig. 3 shows a principle schematic representation of an AFC.

The fuel cell system is made out of several cells called a membrane electrolyte unit and is supplied by supporting and cooling units. The membrane electrolyte unit contains the electrolyte itself and the platinum electrodes. Several cells are arranged and separated by plates and sheets in order to form a stack. Along these sheets the membrane is supplied by the hydrogen, respectively the oxygen and the coolant which has to carry away the generated in the ohmic resistor of the electrolyte. This is the activation and polarisation energy of the chemical reactions. A detailed view of the cross section of a fuel cell is drawn in fig. 4.

The hydrogen fuel is stored in liquid form in a cryogenic container. When leaving the container, the hydrogen is vaporised and brought to anadequate temperature in order to supply the cells. Furthermore, an oxygen tank, regulating facilities for temperature and pressure, controlling units for forced cooling, pumps and compressors have to be installed to maintain the cell.

These supplying facilities have to be fed by an external battery [10]. The source of this energy can be the board battery as presented for handling the peak loads of the traction drive.

Nowadays, efforts to replace the pure oxygen by normal air are performed. The air is sucked in by a compressor and filtered in order to make the oxygen tank unnecessary.

An advantage of the fuel cell system is its modular stack design. Referring to the current/voltage characteristic of a single stack of the fuel cell system (fig. 5), the optimum operating point, e.g. the

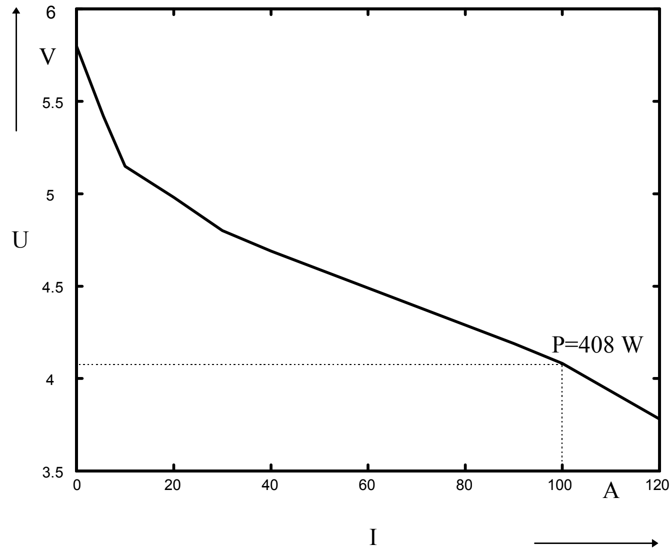

Fig. 5 Current / voltage characteristic of one stack

point of maximum output power, can be found at V=4.08 V, I=100 A, P=408 W.

Combining 30 fuel cell modules together, the rated power of the entire system is 12.2 kW. Considering the consumption of the fuel cell system itself of about 2 kW, the net available power for the traction line yields the required value of 10 kW.

The modules can be connected in series or parallel to obtain a supply voltage of 122.4 V with 100 A or 61.2 V with 200 A or 40.8 V with a maximum current of 300 A respectively. In order to reduce the effect of parasitic currents, two parallel paths are chosen. However, a current of 200 A forces thermal losses and public authorities have difficulties to license the vehicle.

The fuel cells are assigned to provide a continuous and steady energy flow. In addition to this, they only can handle a maximum variation of 5 A/s. Consequently rapid changes have to be absorbed by the board battery respectively transformed into thermal energy by a resistance. The generated heat can be used for the heating system inside the vehicle.

A small disadvantage of the fuel cell supplied electric vehicle can be seen in its starting procedure. It takes three minutes to start the system and a further three minutes until the electrolyte has reached its operating temperature of approximately 70°C. At room temperature the fuel cells are providing about half of the rated power.

To reduce the overall weight of the system, the board net battery must have a high value of energy density. This gives preference to the NiCd batteries compared to the Lead-Acid systems, although they are more expensive. In table 2 a collection of typical parameters of different battery systems can be found. To obtain the high current demand during the overload operation of the drive-train the board battery must have a low internal impedance to avoid collapsing of its terminal voltage under load.

The NiCd cells meet this requirement with its lower internal impedance compared to the other battery systems.

Table 2 Typical parameters of different types of batteries [8]

Battery system	Lead	NiCd	NiH	NaS
Energy density [Wh / kg]	30	50	60	60
Power density [W / kg]	80	200	200	110
Max. number of cycles	800	2000	2000	1500
Range	low	medium	high	high

The NiH and NaS battery systems posses a higher energy density compared to the before mentioned NiCd and Lead-Acid batteries. Lead-Acid and the NiCd battery are operating at room temperature. In contrast to this, the NiH and the NaS batteries are operating at levated temperatures in the range of 300 ºC.

4. Modular drive concept

The main parts of the drive equipment of an electric vehicle are the traction energy source, for the fuel cell, the converter with traction motor and controller, a rechargeable board battery and the main controller. Each drive module is connected to a main controller to collect information of the status of the single module. Information about the desired torque T_d by the driver of the vehicle is processed by the main controller. The supply voltage of the fuel cell U_{fc} is monitored as well.

The rated power of 10 kW must be fully provided by the fuel cell linked to the bus by a dc-inverter as well as a 180 V battery in order to get a constant bus voltage of 300 V. Figure 6 shows the modular drive topology foreseen for this type of non-conventional supply.

A capacitor has to be applied to the inverter bus voltage in order to handle overvoltages. It has to be able to absorb peaks of more than 125% of the rated bus voltage. The resistor has to dissipate the braking energy by the motor if recharging of the board net battery is not recommended. The permanent magnet synchronous motor is controlled by a voltage-source PWM-inverter. As long as the motor requires energy and the battery is not fully charged, the fuel cell is running continuously generating the rated output power of 10 kW to supply the motor or / and to charge the battery. Oscillations in the demand of traction energy and power needed during overload operation are provided by the board battery. The generated energy during braking operation is used for recharging the board battery. If recharging of the battery is not demanded, the generated energy is absorbed by the resistor.

The heart of the drive-train consists of the alone mentioned permanent magnet excited synchronous machine. In the past variable speed drives have been dominated by the dc machines. This is due to its simple control structure and the low converter expenses. With ongoing developments in power electronics and

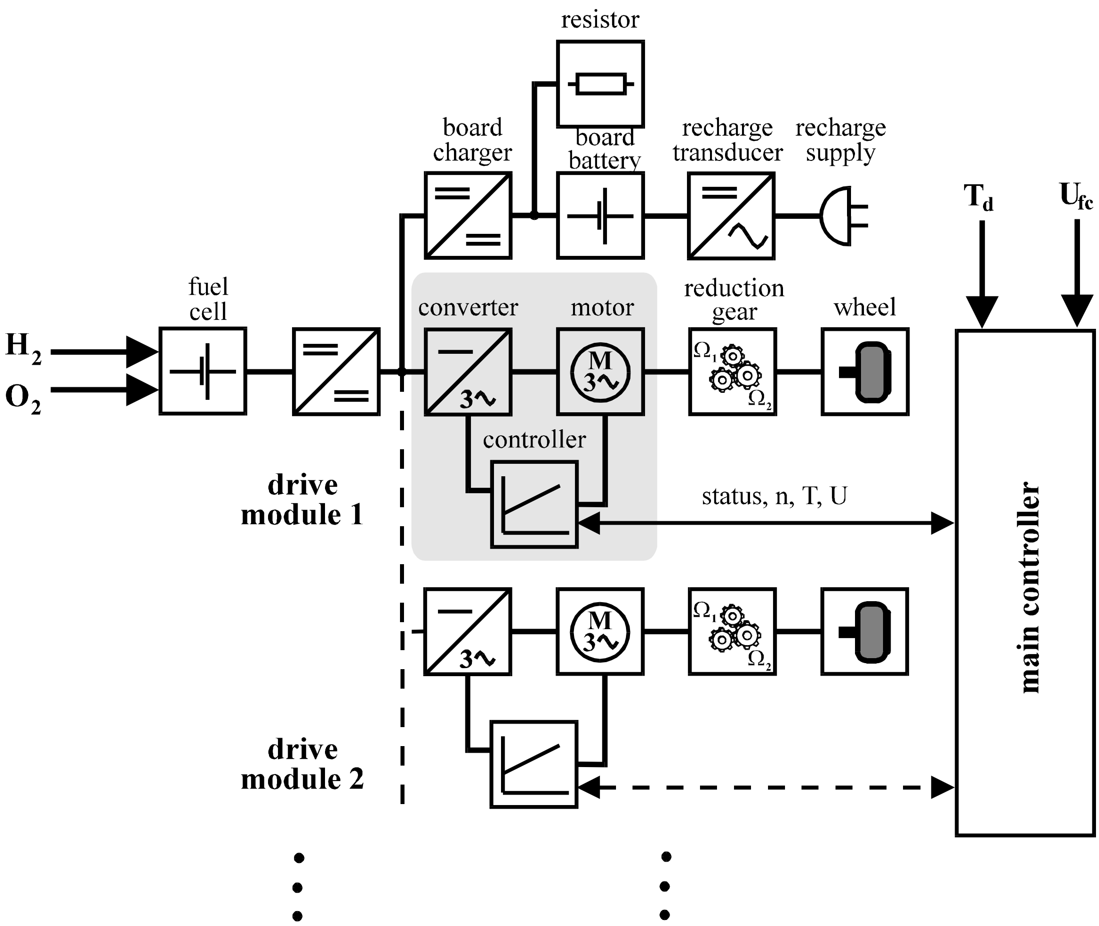

Fig. 6: Topology of the modular drive concept

their components, regarding possibilities and the price as well, the conventional dc machine is partially substituted by three phase induction motors and permanent magnet excited servo machines. With the developments in rare earth permanent magnet technologies, the inset of high energy and high quality motors with a low ratio of weight to volume is possible.

The separately excited dc motor with mechanical commutator is widely used on the account of its good dynamic and static behaviour. However, its application is limited to speeds below 10.000 RPM. In order to achieve a high speed drive to reduce volume and weight at the same output power, it is necessary to replace the mechanical commutator by an electronic one. A electronically commutated machine offers the advantage of a long lifetime, low maintenance, low audible noise, wide speed range, easy speed control, high pull out torque, high efficiency and suitability under extreme conditions. The basic failure rate of brushless motors is much lower compared to motors with brushes. In the brushless type of motor the armature winding is transferred to the stator and the exciting field winding is replaced by a permanent magnet system situated on the rotor.

The high efficiency of the permanent magnet synchronous machine (brushless ac machine) due to the absence of losses generated in the exciting field, winding, makes this type of motor advantageous for application supplied by batteries. In recent years the permanent magnet brushless dc motor has been the first choice in the drive-train of electric vehicles. The brushless ac motor however seems to become the standard in the next few years. So the advantages and disadvantages of these two systems are discussed briefly.

The armature of a brushless dc motor consists of a multiphase winding. For economic reasons, three or four phases are used normally. The electronic commutation circuit is realised by electronic switches (transistors, FET's, MOSFET's). These switches are controlled in the way that they are switched on or off in pace with the position of the rotor to give the maximum torque. For the detection of the rotor position simple optoelectronic, HALL generators, field plates or search coil sensors are used. Due to the switching of the windings to the supplying energy source, the time depending winding current is block shaped. Combined with the permanent magnet excited rotor field the resulting torque is superposed by a torque ripple.

In a brushless ac motor the terminal current is sinusoidal. Depending on the individual rotor construction, the shape of the rotor field can mainly be found in a block shape. With the use of a distributed three phase stator winding, the induced voltage becomes sinusoidal. Therefore, the machine generates a time and position independent constant torque. Due to a less content of harmonics in the air gap field compared to the brushless dc motor, increased values of efficiency are. Furthermore less torque ripple and audible noise are generated. However, a much more precise and so expensive position sensor is required to control the machine behaviour.

To summarise, it can be stated that a brushless dc permanent magnet excited synchronous motor is cheaper and easier to control compared to the ac type of machine. On the other hand a brushless ac motor offers a higher efficiency and a better comfort.

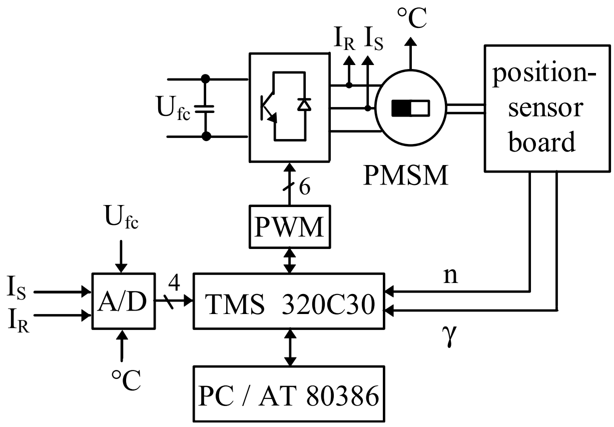

Fig. 7 Control scheme of the brushless ac motor

5. PWM-inverter

The permanent magnet excited synchronous motor (PMSM) is supplied by a switch-mode inverter based on IGBT technology. The high switching rate of the power electronic components is important, especially when a PMSM with sinusoidal waveform is considered. The high switching frequency of IGBTs ensures that even at high motor speeds the distortion of the current waveform with respect to the reference signals is minimal. When switching frequencies up to 20 kHz are available, the audible noise level can be substantially reduced.

Both, for sinusoidal and trapezoidal wave form PMSM's, a current-regulated VSI is used. The DC input voltage is said to be nearly constant at 300 V.

As mentioned above, controlling the inverter is somewhat more complex in the case of a PMSM with sinusoidal waveform. An absolute position sensor such as a high-accuracy resolver is required.

The research and development of the control strategy is done on a PC platform equipped with a Digital Signal Processor (DSP) board and additional analogue I/O cards (fig. 7). As DSP a TMS 320C30 by Texas Instruments, which is working with 33 MFLOPS is used.

In order to protect the permanent magnets from demagnetisation, the temperature in the motor is checked by thermo-elements. Therefore 12 P_t-100 temperatur sensors are placed in the stator.

6. Conclusions

A concept for a drive-train applicable for zero emission electric vehicles equipped with fuel cells is introduced. A modular system of single drive systems consisting of an inverter, with its motor and control leads to an overall system able to be applied to transport system with different power ranges. The specific operating behaviour and requirements for this non-conventional supply of a variable speed drive is discussed. Further investigations and the planned prototyping of this type of drive system will generate improvements in the design and will uncover shortcomings as well.

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References

[1] Allen, T., Monkhouse, P.J., Mellor, P.H. and Howe, D.: "An advanvced brushless permanent magnet drive system for an all-electric racing car", *Proc. 13th Intern. Workshop on Rare Earth Magnets and their Applications*, Birmingham, UK, 1994, pp. 673-681.

[2] Vermeulen F.: “Characterisation of PEM fuel cells for electric drive trains”, *Electric Vehicle Symposium 12*, Annaheim USA, 1994, pp. 439-447.

[3] Slemon, G.R.: "Electrical machines for variable-frequency drives", *Proceedings of the IEEE*, Vol. 82, No. 8, August 1994, pp. 1123-1139.

[4] Hoang, Le-Huy: "Microprocessors and digital IC's for motion control", *Proceedings of the IEEE*, Vol. 82, No. 8, August 1994, pp. 1140-1163.

[5] Van Wyk, J.D.: "Power electronic converters for motion control", *Proceedings of the IEEE*, Vol. 82, No. 8, August 1994, pp. 1164-1193.

[6] Fijalkowski, B.T. and Trovato, K.I.: "A concept for a mechatronically controlled full-time 4WD x 4WB x 4WA x 4WS intelligent vehicle for drives with special needs", *Proc. of the dedicated Conf. on Mechatronics and Supercomputing Applications in the Transportation Industry,* 1994, pp. 161-172.

[7] Rajashekara, Kaushik: "History of electric vehicles in GENERAL MOTORS", *IEEE Transactions on Industry Applications*, Vol. 30, No. 4, July 1994, pp. 897-904.

[8] Hadschi-Milanglou J.-R.: “*Antriebskonzepte mit permanent-erregten Synchronmotoren für den Einsatz im Elektrofahrzeug*”, Ph.D. RWTH Aachen, June 1994.

[9] Chan, C.C.: "An overview of electric vehicle technology", *Proceedings of the IEEE*, Vol. 81, No. 9, September 1993, pp. 1202-1213.

[10] Hodkinson R.L.: “45 kW integrated vehicle drive”, *Electric Vehicle Symposium* 11, Florence Italy, 1992, pp. 8.04/1-8.

[11] Maggetto, G.: "Advanced drive systems and infrastructure for electric or hybrid buses, vans and passenger cars (I)", *EPE Journal*, Vol. 2, No. 2, June 1992, pp. 71-76.

[12] Maggetto, G.: "Advanced drive systems and infrastructure for electric or hybrid buses, vans and passenger cars (II)", *EPE Journal*, Vol. 2, No. 3, October 1992, pp. 145-156.

[13] Maggetto, G.: "Advanced drive systems and infrastructure for electric or hybrid buses, vans and passenger cars (III)", *EPE Journal*, Vol. 2, No. 4, December 1992, pp. 211-224.