Sustainable transport system using renewable energy and efficient electric vehicles

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Abstract

The most environmentally friendly model for a transportation system, based on the available technology, could involve the use of zero emission electric vehicles combined with a highly efficient electrical drive system and an electrical storage system that can be replenished using renewable energy sources.

This paper presents the overall strategy of a transportation system. It presents a model for the dynamics and drive of an electric vehicle, describes a novel approach for optimising the efficiency of induction motor drives, reports on practical evaluations of an electric vehicle drive under controlled laboratory conditions and relates the application of renewable sources of electrical energy to the transport sector.

The results demonstrate the feasibility of the use of efficient electrical drive systems coupled with renewable energy sources as a strategy for a zero emission transportation system.
Keywords: transport systems, zero emission, sustainability, electric vehicle, renewable energy, energy management, induction motor.

1 Introduction

This paper represents part of the findings of a comprehensive research project related to a sustainable transport system using renewable energy and efficient electric vehicles. As pollution of the environment has become an important concern for all societies and a major contributor to global warming, the search for sustainable zero emission transport systems is becoming increasingly important. Some 30% of the overall CO_2 emission in Europe is produced from transport and use of vehicles for domestic and commercial purposes is rising

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significantly. Increased traffic volumes in developing countries can only add to overall CO_2 emissions. This has made the emphasis on cleaner methods of transportation essential and promotes the use of electric vehicles that do not directly emit any pollutants in operation [1]. New portable energy storage systems, such as hydrogen fuel cells, are becoming more viable and increased investment in sustainable energy generation, especially by wind and solar, could lead to a future transport system that is much less damaging to the environment than is the case currently [2,3].

In order to reduce the cost and time of development, a computer simulation model has been utilised using real system parameters to investigate different control strategies.

A MATLAB model has been developed to evaluate the energy budget of an electric vehicle over defined driving cycles such as city, urban and motorway [4]. The model demonstrates that an improvement in the efficiency of electric drives is of considerable benefit to the electric vehicle as this will reduce energy consumption directly and indirectly by allowing weight saving of batteries, motor and support structure of vehicles. It also demonstrates the improvements to be gained from introducing other initiatives into the design of an electric vehicle such as lightweight composite materials for the vehicle body, dynamic control systems designed for efficiency and high efficiency lights. A test rig, employing an induction motor drive and a further motor as a dynamic load, has been constructed to enable the practical evaluation of an electric vehicle drive and to test, under controlled laboratory conditions, the energy demands of an electric vehicle over defined driving cycles [5].

This paper presents the analysis results of the MATLAB model of the energy budget of an electric vehicle. It clearly demonstrates the advantages of improved motor drive efficiencies and demonstrates the advantages offered by regenerative braking and the introduction of other energy saving initiatives. An overview of the sustainable generation and storage of electrical energy is also given in relation to the energy demands of an electric vehicle. The specifications of a sustainable power generating plant to supply the energy demands of an electric vehicle in daily use is described in terms of the sizes of photovoltaic and wind electrical generators.

2 Mathematical model and laboratory test rig of the electric vehicle

The mathematical model of the electric vehicle is based upon MATLAB Simulink and enables the theoretical evaluation of the mechanical demands and energy requirements of the vehicle over defined driving cycles. The laboratory test rig consists of an ac induction machine, representing the vehicle motor, mechanically coupled to a d.c. machine, representing the total load presented to the vehicle motor due to rolling resistance, gradient resistance, aerodynamic resistance, vehicle acceleration and frictional losses in the drive train. The characteristics of the vehicle motor are measured on the test rig and are fed into the model. The model and laboratory test rig are then operated over the same driving cycle and the results compared. With the model verified by laboratory measurement, it may then be applied to a range of driving cycles and vehicle parameters with some confidence.

2.1 The MATLAB Simulink mathematical model

The model inputs consist of vehicle parameters, a defined driving cycle (speed and gradient), electrical drive parameters, power efficiencies of components, regenerative characteristics and equations to describe the control strategy adopted for the electrical machine drive. The outputs consist of driving wheel speed and torque demands, the mechanical demands placed on the electrical machine, the power demands and regenerative power supplied to the battery, a complete energy budget for the vehicle detailing the energy consumption of all components and battery energy drain and allows the range of the vehicle obtainable from a fully charged battery set to be determined.

2.2 The laboratory test rig

The electric vehicle drive consists of an induction machine with switchable 1 or 2 pole pairs rated at 240V, 50Hz and 4kW. A pair of these machines is suitable for a small vehicle, although results can be scaled for other vehicle sizes. The switchable pole pair arrangement gives the vehicle two electrical gears. A variable voltage variable frequency drive is used which allows for the adoption of defined electrical drive strategies. The mechanical load is provided by a torque controlled d.c. machine. The rig is under real time computer control using a p.c. programmed in c++. The test rig operates over driving cycles defined in terms of a speed and gradient profile. Extensive measurements are made during operation allowing the overall energy efficiency of the vehicle to be determined.

3 The efficiency of the electric vehicle

The efficiency of the electric vehicle is defined as:

$$n_{drive} = \frac{P_{mech}}{P_{elecout}} \tag{1}$$

where: P_{mech} = mechanical power provided to the vehicle driving wheels
$P_{elecout}$ = gross electrical power supplied by the battery set

The gross electrical power supplied by the battery set includes the power required for the electrical machine drive, control electronics, lights, ancillary electrical and electromechanical components and other losses.

During periods of deceleration and downhill travel regeneration can occur and mechanical power from the driving wheels used to charge the battery set. The regeneration efficiency is defined as:

$$n_{regen} = n_{batt} \frac{P_{elecin}}{P_{mechin}} \tag{2}$$

where: P_{mechin} = mechanical power available at the vehicle driving wheels
P_{elecin} = gross electrical power supplied by the battery set
n_{batt} = efficiency of battery charge/discharge process
Integrating the power measurements over the time of a driving cycle enables the overall energy budget to be evaluated.

An improvement in the efficiency of electric vehicle drives is of considerable benefit as this not only reduces drive losses directly but also allow weight saving of batteries, motor and support structures, reducing the electrical energy required from the battery set even further. The vehicle drive is required to supply wide ranges of torque throughout a wide range of speeds, including the high torque and low speed demanded for climbing hills and low torque and high speed demanded during downhill motorway driving. For maximum operating efficiency, the operating conditions of the vehicle drive must track the maximum efficiency point throughout the driving cycle.

3.1 Electric vehicle drive control for maximum efficiency operation

The laboratory test rig and simulation model are used to identify the most efficient operating conditions for the electrical drive to provide a demanded torque and speed. Figure 1 shows the results of practical tests made on the laboratory test rig. It clearly identifies the drive voltage required in order to achieve maximum efficiency operation whilst meeting a mechanical demand of 10Nm torque and a shaft speed of 1040rpm, representing a vehicle speed of 23.5kph when a driving wheel diameter of 0.6m and gearing ratio of 8:1 is used. It clearly shows that greatest efficiency is obtained when the supply voltage to the machine is approximately 100V rms.

Simulation and laboratory tests show that optimising the voltage level for changes in load and speed provide an improved efficiency performance that could lead to energy savings of up to 33.7% [6], particularly over routes that consist of large periods of constant speed where the power demand of the vehicle drive is less than 50% of its maximum rated power.

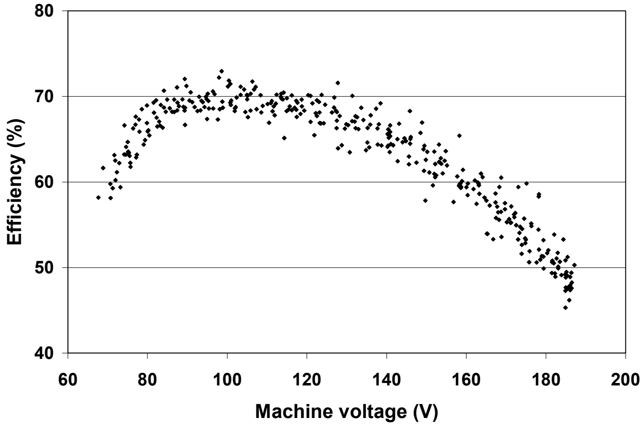

Figure 1: Drive efficiency as a function of voltage.

4 Energy requirements of vehicles

In order to evaluate and compare typical energy demands for transport vehicles, a set of realistic driving cycles, describing vehicle speed as a function of time, is adopted. The European congested urban cycle describes a vehicle journey of 1705m in a time of 428s on a route heavily congested with other vehicles (figure 2) and the European free flow urban cycle describes a vehicle journey of 2226m in a time of 355s on a route influenced by traffic management systems (figure 4). The European motorway cycle describes a journey of 12672m in 452s. A set of four typical vehicle specifications is also adopted (table 1). The energy required to propel the vehicles using optimum efficiency drive control techniques over the driving cycles as calculated by the simulation model is given in table 2 and shown in figures 3 and 5.

Table 1: Vehicle specifications.

	Scooter	Rickshaw	Small car	Large car
Weight (kg)	140	300	750	1500
Frontal area (m^2)	0.9	1.2	1.8	2.2
Drag resistance Cd	0.38	0.35	0.31	0.28
Rolling resistance, Kr ($N.kg^{-1}$)	0.013	0.014	0.015	0.017

Table 2: Vehicle energy demand.

Vehicle	European congested urban cycle.	European free flow urban cycle.	European motorway cycle.
Scooter	125.1 kJ	223.2 kJ	
Rickshaw	226.8 kJ	383.1 kJ	
Small car	506.9 kJ	811.5 kJ	7656.6 kJ
Large car	1005.4 kJ	1559.8 kJ	10890.3 kJ

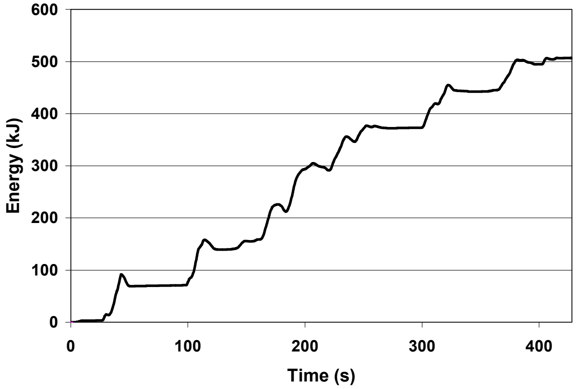

Figure 2: European congested urban driving cycle.

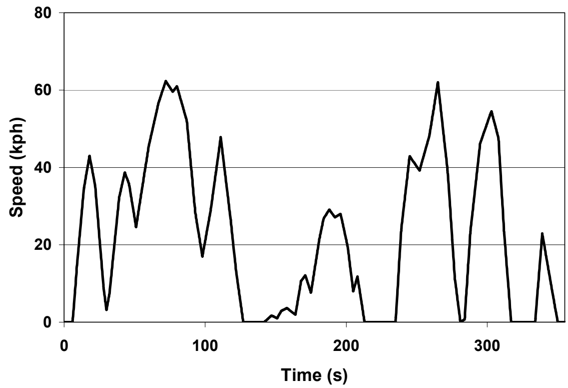

Figure 3: Energy required from battery set by small car during European congested urban driving cycle.

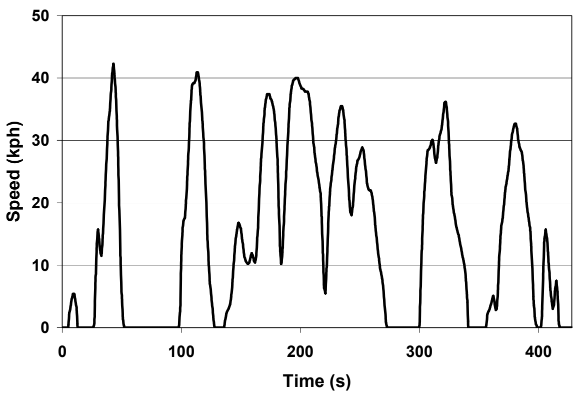

Figure 4: European free flow urban driving cycle.

5 Generating energy for electric vehicle transport system from sustainable sources

Consideration is given to the size of power generating plant capable of supplying sufficient electrical energy to a small vehicle for typical car usage. In the UK during 2004, the average distance travelled by a person in a car or van was 5583km as a driver and 3217km as a passenger, with 28% of journeys related to work, 6% for education purposes and 23% for leisure [7]. A typical UK family travels some 14000km by car annually. By relating the typical profile of car journeys to the energy demands calculated within the simulation model, a realistic energy requirement to satisfy the average personal vehicular transport for a UK person is 2000MJ and 5000MJ is required to satisfy the demands of a typical UK family using a small car.

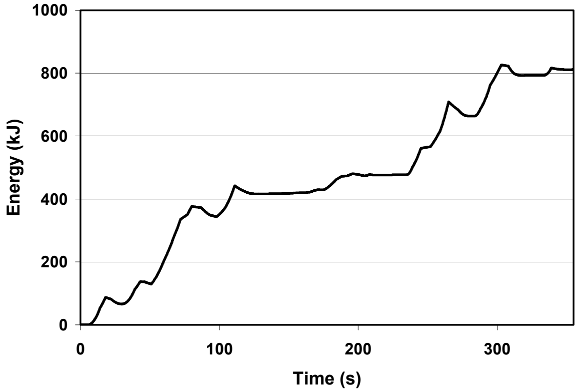

Figure 5: Energy required from battery set by small car during European free flow urban driving cycle.

5.1 Energy generation from wind sources

The total amount of energy available annually from a wind generator depends principally upon its size and location [8]. A wind generator with a rated power of 6kW, blades transcribing a circle of 5.5m diameter and located on a tower of height 10m is considered in one location in England, Nottingham, and two locations in Scotland, Glasgow and Wick. Other inputs are a Weibull factor of 2 for Nottingham and Glasgow and 2.5 for an exposed location in Wick and wind speed data for year 2005. For Nottingham, Glasgow and Wick the average power throughout year 2005 was 451W, 611W and 1376W respectively, representing total energy generation of 14232MJ, 19281MJ and 43422MJ respectively. Approximately 10% of the energy generated will be lost due to transmission and storage. A 5.5m diameter wind generator perched on a 10m tower can therefore supply the energy required for the personal transport of between 7 and 21 UK people or between 3 and 8 UK families.

5.2 Energy generation from photovoltaic sources

Supplying energy to transport systems from photovoltaic sources has been discussed by Messenger [9]. The largest energy density available from the sun at the surface of the Earth is approximately 1kW/m^2. Commercial photovoltaic panels offer a typical conversion efficiency of between 10% and 15%. Conversion efficiencies of photovoltaic panels for the space industry are up to 36.9% efficient [10].

The power available from a photovoltaic panel is dependant on the elevation of the sun above the horizon and weather conditions. A solar panel of 12.8% efficiency in full sun in southern UK at equinox will produce approximately 250Watt.hours or 900kJ of energy per day per m^2 [11]. Weather conditions, seasonal changes and other losses will reduce this to an average of 750kJ per day, or approximately 270MJ per year. Thus the total area of a commercial solar panel required to satisfy the personal transport demands of the average UK person is 7.4m^2 and to satisfy the personal transport demands of a typical UK family is 18.5m^2. In Glasgow, the sizes of solar panels are required to be 16% larger.

Due to the variability of wind and sun, both geographically and seasonally, a strategy based upon generating power by both methods is recommended.

6 Conclusion

This paper has presented the overall strategy of a transportation system. It has presented a model for the dynamics and drive of an electric vehicle, described a novel approach for optimising the efficiency of induction motor drives, reported on practical evaluations of an electric vehicle drive under controlled laboratory conditions and related the application of renewable sources of electrical energy to the transport sector. The results show that a sustainable transport system based upon efficient electric vehicles and sustainable sources of energy is feasible.

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