Switched reluctance drives for electric vehicle applications

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Abstract. Electric vehicles are the only alternative for a clean, efficient and environmentally friendly urban transport system. With the increasing interest in electric vehicles, a great effort is required in order to develop electric drives for electric vehicle propulsion. This paper first tries to explain why the switched reluctance drive is a strong candidate for electric vehicle applications. It then gives switched reluctance drive design guidelines for battery or fuel cell operated electric vehicles. Finally, it presents the design and simulation of a switched reluctance motor power train.

Key words

Electric vehicle, electric drives, power drive train, switched reluctance motor.

1. Introduction

Environmental and economic considerations are the major reasons for the development of electric vehicles. Exhaust emissions from the internal combustion engine are the main source of urban pollution and one of the most important causes of the greenhouse effect. The pollution problem only gets worse with increasing numbers of automobiles. There is also an economic factor arising from the poor energy conversion efficiency of the internal combustion engine. When efficiency is evaluated on the basis of conversion from crude oil to road load at the wheels, the numbers for electric vehicles are not significantly higher than for internal combustion engine vehicles (19.64% for electric vehicles, 10.26% for internal combustion engine vehicles). Moreover, efficient power generation at electric plants together with very high motor and controller efficiency and advancements in power source technology within the vehicle, battery or fuel cell, mean that electric vehicles offer huge possibilities for improving overall efficiency.

This paper shows the capabilities of switched reluctance motors as a power train for battery or fuel cell operated electric vehicles and gives design guidelines. The paper is divided into six sections. Section 2 summarizes basic electric vehicle dynamics and gives drive specifications. Different alternatives to electric drives for electric vehicles are presented in Section 3. Section 4 revises the relationship between switched reluctance motor drives and electric traction, and gives design guidelines for sizing switched reluctance motors for electric vehicles. A design proposal for a switched reluctance motor and the simulation of its specified car performances is presented in Section 5, and the conclusions in Section 6.

2. Basic electric vehicle dynamics and drive specifications

The motive force at the wheels or road load, *F,* consists of gravitational force, rolling resistance of the tyres, aerodinamic drag force, and acceleration force, that is [1].

$$F = (c_0 + \sin\beta)mg + 0{,}5\rho C_D S(v + v_0)^2 + k_m m\frac{dv}{dt} \qquad (1)$$

where c_0 is the tyre rolling resistance, β is the angle with respect to the horizontal, m is the gross mass of the vehicle, g is the acceleration due to gravity, ρ is the air density, C_D is the aerodynamic drag coefficient, S is the vehicle frontal area, v is the vehicle speed, v_0 is the head-wind speed and k_m is the rotational inertia coefficient. In this paper the parameters affecting drive performance are fixed at the following values: Gross weight around 1500 kg, cruising speed 120 km/h, maximum speed 180 km/h, and a gradability or climbing capability of about 40%. These performance parameters are typical for a subcompact car powered by a 1600 to 1800 cm^3 gasoline internal combustion engine. The choice of the power train for these performance parameters is based on the road load to speed envelope derived from equation (1), see Figure 1. Recent studies reveal that operational constraints on vehicles, such as initial acceleration and gradability, can be better meet with a minimum power rating if the power train can be operated mostly in the constant power region [2],[3].

Electric vehicles should be designed and controlled to optimize efficiency and regenerative braking. With the advances in power electronics, high efficiency operation in different road conditions can easily be achieved by electronic means rather than mechanical means and therefore a fixed gear ratio between the propulsion motor and driving wheels is used [4]. The choice of a suitable reduction factor involves aspects such as motor size,

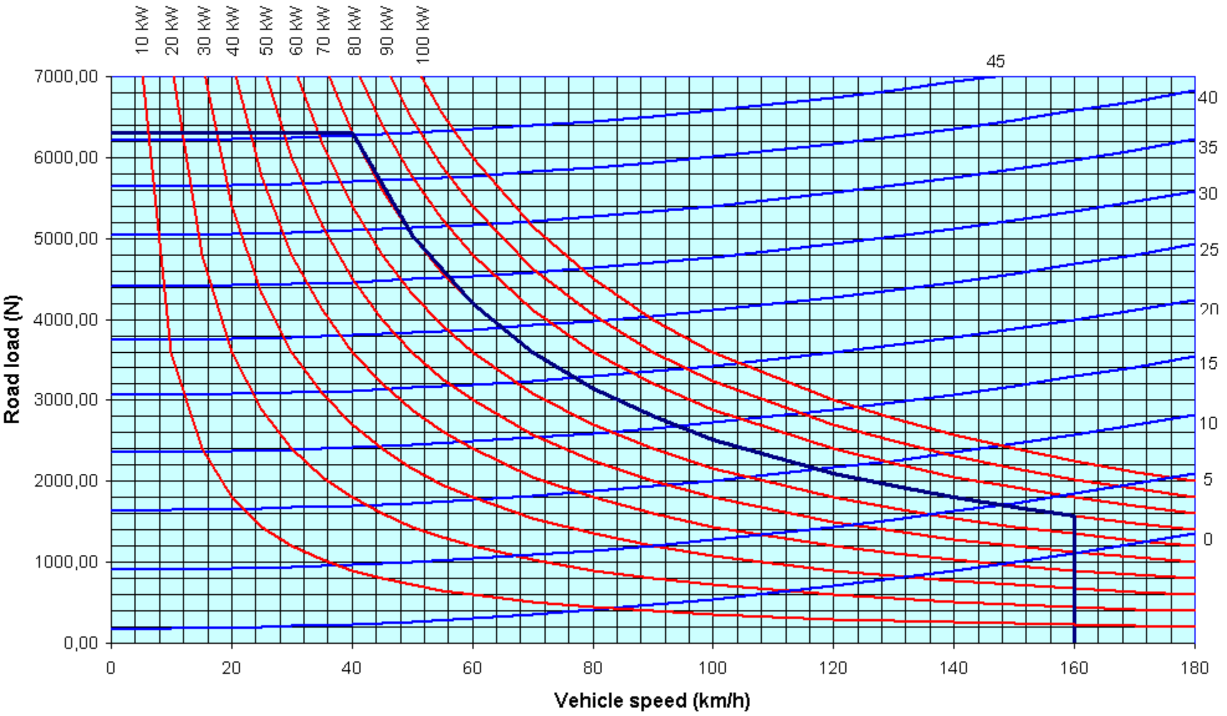

Fig. 1. Road load-speed envelope. In red, lines of equal power (10 to 100 kW); in blue road load vs. speed for different percentage gradabililty (0 to 40%).

size, maximum frequency and power loss, mainly in the iron core but also in the power converter. Appropriate values for a wheel radius of 0.3 m, are between 5 and 12. Electric propulsion demands an energy source that could be advanced batteries (NiMH or Li-ion) or preferably a fuel cell (PEM) [5],[6]. The voltage at D.C. bus must be higher than 300 V D.C., but if this voltage is not regulated, rated power and torque must be fulfilled at minimum voltage. Therefore, taking into account the above car performance parameters, the drive specifications should be: Power 75 kW, Maximum torque 220 Nm, Base speed 3200 rpm, Maximum speed around 12500 rpm, Constant power operating range 4 times base speed, and Gear ratio 9. Figure 2 shows the motor shaft torque versus rotor speed profile, and indicates the different operating zones. Additional requirements are four quadrant operation, overload (at least 50% of maximum torque for 90 s duration), high efficiency (>85% in almost all operating conditions, and even >90% at rated conditions), and low weight.

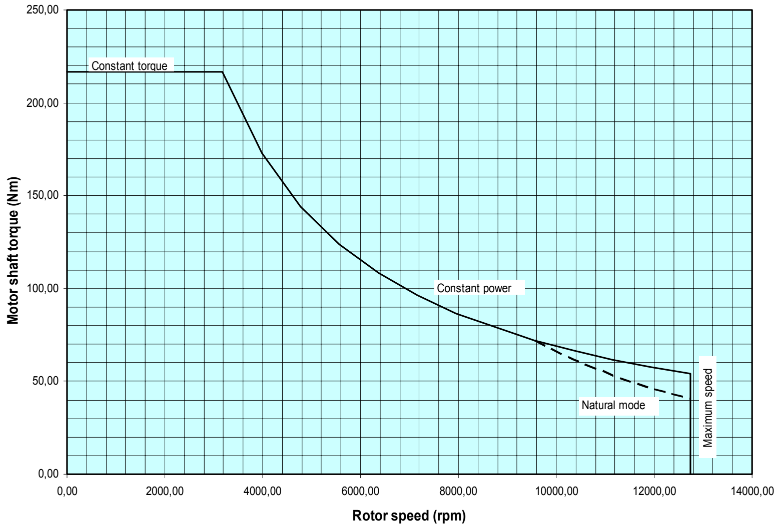

Fig. 2. Motor torque-speed profile

TABLE I.- Comparison of BDCMD, SPMMD, SRMD and IMD for electric vehicle application

Items	Maximum	BDCMD	SPMMD	SRMD	IMD
Power density	10	9	10	8	7
Overload	10	7	7	8	9
Efficiency	10	9	10	8	7
High speed range	20	10	16	18	16
Control	20	15	15	16	16
Noise	10	8	8	6	8
Torque ripple	10	6	8	5	7
Size and weight	10	8	9	7	7
Ruggedness	20	14	14	17	16
Maintenance	10	8	8	9	9
Manufacturability	20	14	12	18	16
Cost	30	20	18	26	28
Total	180	128	135	146	146

3. Electric drives for electric vehicles

In selecting an electric drive for electric vehicles, considering single power train, the following items were considered: power density, overload, efficiency, high speed range, control, noise, torque ripple, size and weight, ruggedness, maintenance, manufacturability and cost. Nowadays, several electric drives fulfil requirements in these categories: Brushless D.C. drives (**BDCMD),** Synchronous permanent magnet motor drives (**SPMMD**), Switched reluctance motor drives (**SRMD**), and Induction motor drives (**IMD)**. The choice of the best candidate involves weighting the requirements according to a specific standard of desirability [7]. In this paper, points are awarded for each one of the requirements: maximum points indicate the drive that best meets the requirement. From Table I, the best placed challengers are induction motor drives and switched reluctance motor drives. After recognizing that the two drives have similar merits, we selected a switched reluctance motor because ruggedness (robustness, reliability and fault tolerance capability) and manufacturability (simplicity of laminations. absence of magnets and concentrated windings) are very important qualities for mass production of motor drives for electric vehicles.

4. Switched reluctance motor drive for electric vehicle

A. Switched reluctance motor drive and electric traction

Switched reluctance motor have always been related to electric traction. The first documented switched reluctance motors appeared in the period 1837-1840, and one of their earliest applications (as in Robert Davidson's design) was powering a locomotive on the Glasgow-Edinburgh railway. However, the rapid development of D.C. motors in the second half of the 19th century soon eclipsed switched reluctance motors. The appearance of solid state controlled interrupters started to renew interest in switched reluctance motors, but the modern era of switched reluctance motors did not begin until the late 1970s thanks to a research project on battery powered electric vehicles carried out by the Universities of Leeds and Nottingham and sponsored by Chloride Technical Ltd. [8],[9]. In recent years several important automobile manufacturers have been developing switched reluctance motors as drive trains for their prototype electric cars [10]-[16].

B. Switched reluctance motor drive, some design guidelines

Sizing the Switched reluctance motor

Switched reluctance motor for electric cars need to exploit their advantages to the full while overcoming their disadvantages, mainly torque ripple and acoustic noise. Switched reluctance motors for electric vehicle need a high power density. Therefore, torque per rotor volume values of 40 to 70 kNm/m^3 should be applied in the initial sizing stage. This entails high values of magnetic and electric loading. Although a magnetic material with high saturation flux density is selected, magnetic loading cannot increase very much, so electric loading must reach very high values. As a consequence, high current densities (from 16 to 20 A/mm^2) should be used, the slot fill factor should be more than 50 % and liquid cooling is mandatory. The airgap should be as small as mechanical tolerances allow.

Electric vehicles need to have an extended constant power range. A reasonable margin is 3 to 4 times base speed a margin within the capabilities of switched reluctance motors.

Suitable selection of the number of phases and poles is very important in order to meet expected motor performance parameters. Different combinations of stator/rotor pole number have been proposed for switched reluctance motors for electric vehicle applications: 6/4, 12/8 and 24/16 for three phase motors, and 8/6 and 16/12 for four phase motors, see Table II. Many factors are involved in the choice: the number of power interrupters, the number of strokes, the inductance ratio, the energy conversion area, the switching frequency, cooling of the coils, and acoustic noise. Options with a multiplicity of one reduce Hz/rpm but are clearly noisier, while in options with high multiplicity the disadvantages tend to outweigh the advantages.

TABLE II.- Stator/rotor pole number combinations

Stator/rotor pole number	Number of phases	Multiplicity	Number of poles per phase	Stroke angle (º)	Number of strokes per revolution	Switching frequency per rpm (Hz/rpm)
6/4	3	1	2	30	12	1/15
12/8	3	2	4	15	24	1/7,5
24/16	3	4	8	7,5	48	1/3.75
8/6	4	1	2	15	24	1/10
16/12	4	2	4	7,5	48	1/5

Thin laminations with very high saturation flux density and extremely low iron loss are the best choice but unfortunately the magnetic material closest to meeting these requirements, cobalt iron alloy, is very expensive. The alternative is to use steel laminations with moderate saturation flux density and low iron loss.

Power converter

Numerous different topologies have been proposed for electrical vehicle applications powered by switched reluctance motors [16]. However, the preferred topology consists of an asymmetrical half-bridge or classic converter, with two solid-state power interrupters and two diodes per phase. Due to the current and voltage levels managed, IGBT's are the best choice for solid-state power interrupters. Specific power modules for this kind of converter have not been commercially available up to now.

Control

Complex torque control is required for electric car applications [17]. The Control variables are current amplitude and turn-on and turn-off angles. The control algorithm, implemented on a DSP, should continuously adjust current, turn-on angle, turn-off angle and current amplitude to maintain average torque at the required level, decoupled from D.C. voltage variations and speed changes. Bellow base speed, PWM is used, and in order to maintain torque ripple within tolerable limits current profiling must be considered. Above base speed, in the constant power range and field weakening zone, the only control parameters are turn-on and turn-off angles.

5. Proposed design and simulation.

In order to meet the specifications in Section 2, following the guidelines in Section 4 a 75 kW, 300 V, 12/8 switched reluctance motor prototype was designed, see Figure 3. Table III gives its most important parameters. Figure 4 presents finite element analysis [18] showing flux distribution in aligned and non-aligned positions. Simulink simulation of the drive [19] is shown in Figures 5 and 6.

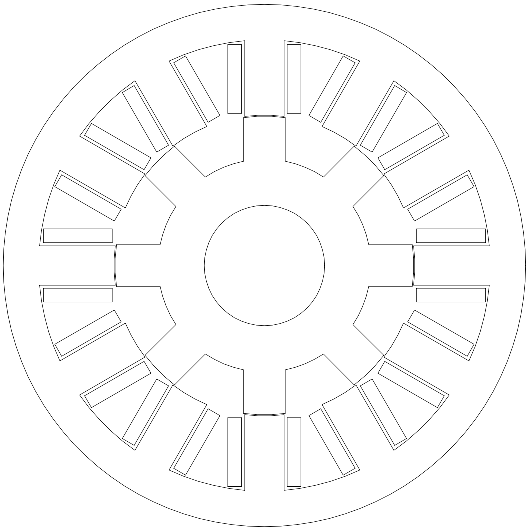

Fig. 3.- 12/8 Switched reluctance prototype

TABLE III.- Main dimensions of the prototype.

Parameter	Value
Number of phases	3
Number of stator poles	12
Number of rotor poles	8
Stator outer diameter (mm)	243
Rotor diameter (mm)	139
Stack length (mm)	243
Airgap (mm)	0.5
Stator pole arc (º)	15
Rotor pole arc (º)	16
Stator pole width (mm)	18.3
Rotor pole width (mm)	19.4
Stator pole length (mm)	35
Rotor pole length (mm)	20
Stator yoke thickness (mm)	16,5
Rotor yoke thickness (mm)	21,5
Shaft diameter (mm)	56
Number of turns per pole	8

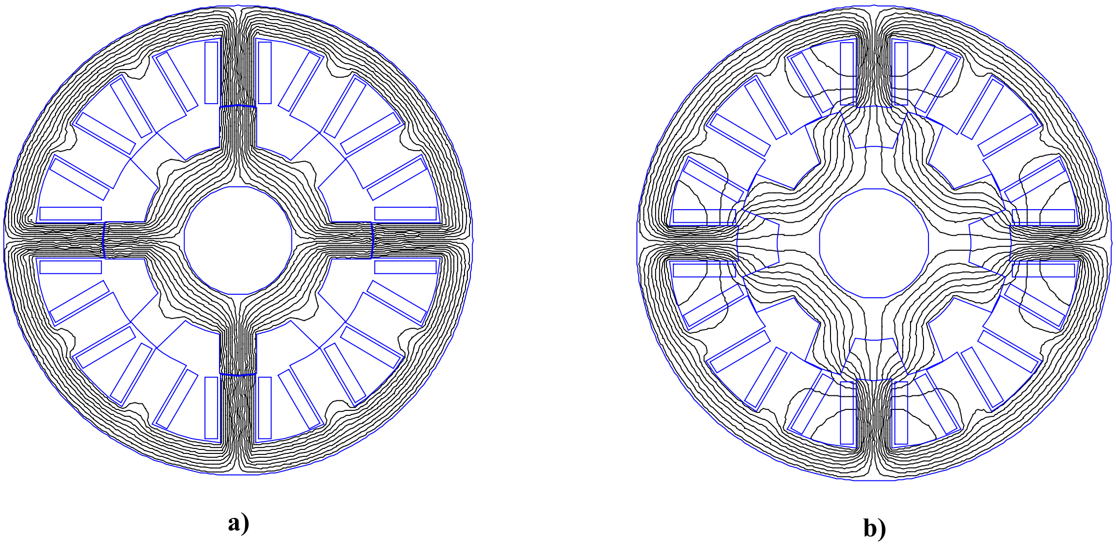

Fig. 4. Finite element flux-plot for 12/8 switched reluctance motor prototype a) aligned position b) non aligned position

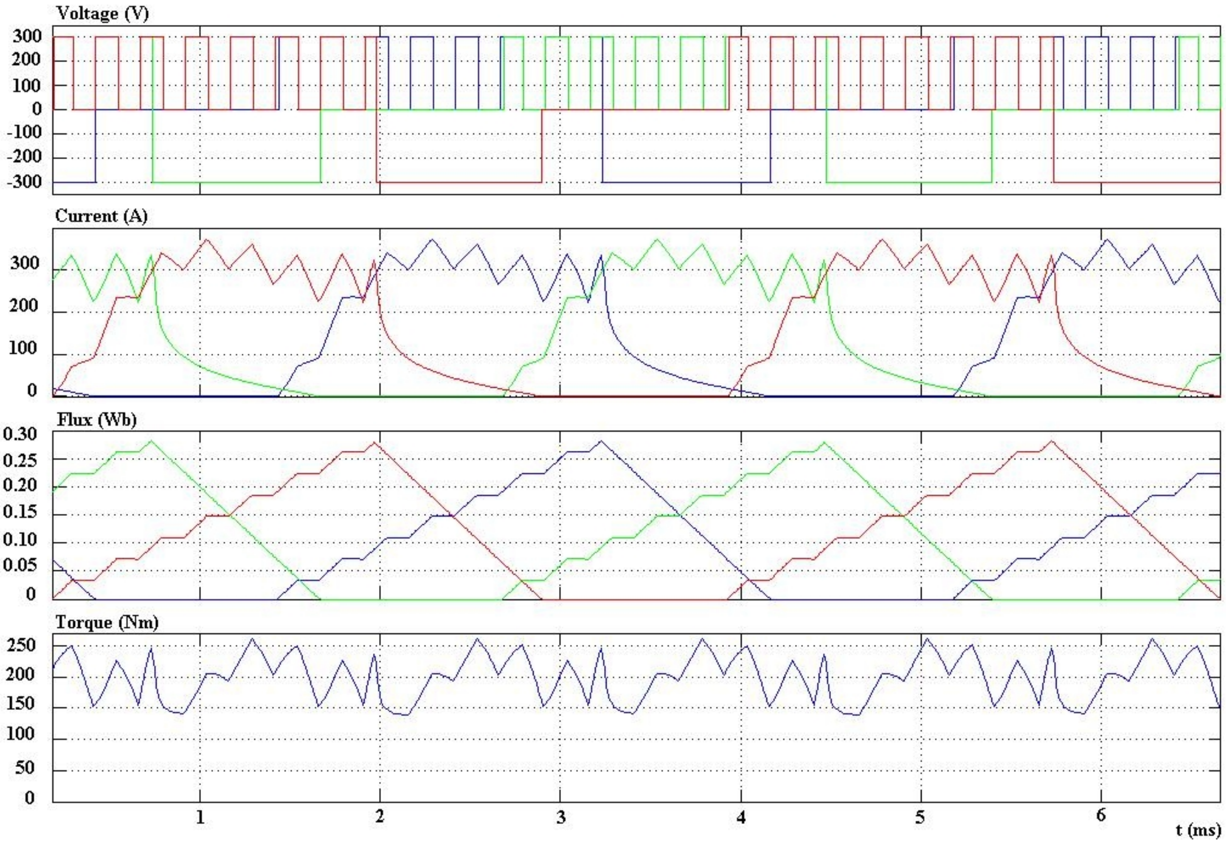

Fig. 5. Matlab/Simulink simulation. PWM control, spped 2000 rpm

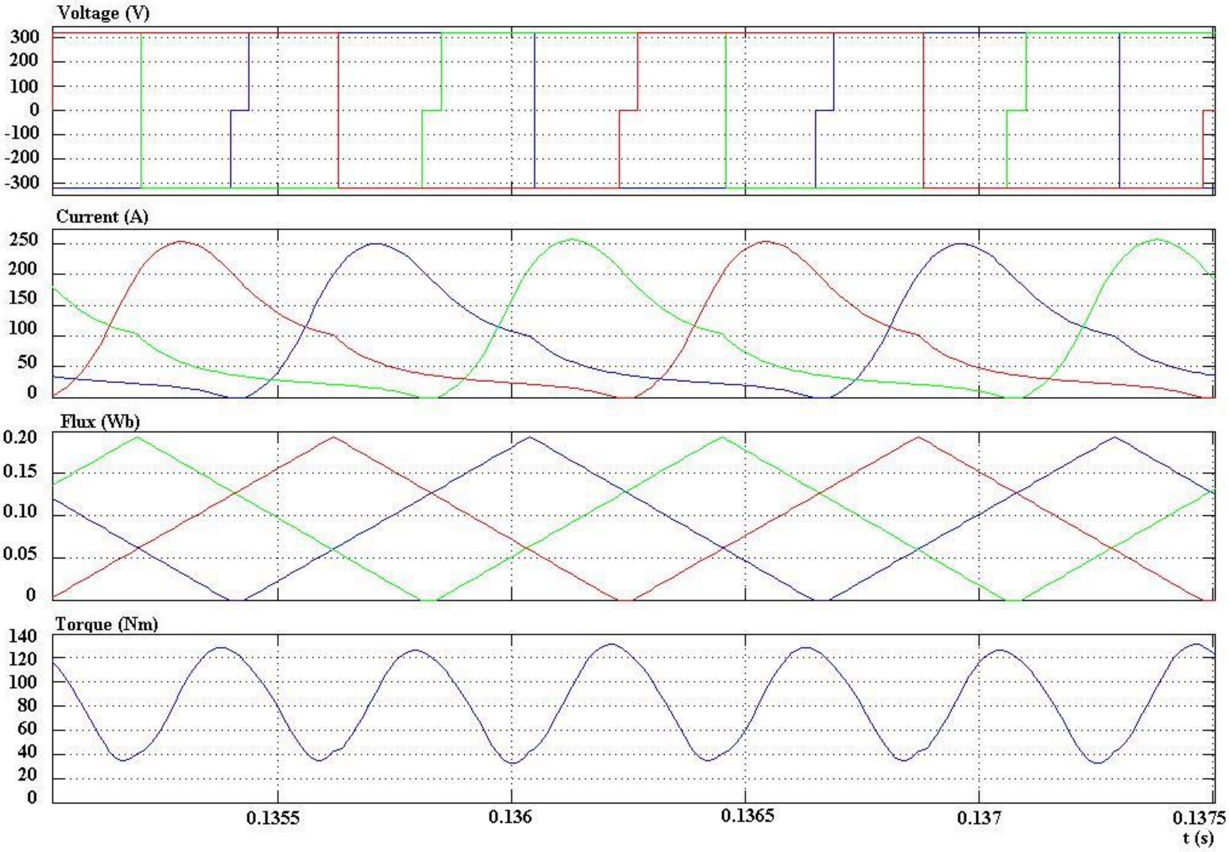

Fig. 6. Matlab/Simulink simulation. Single pulse control, speed 6000 rpm.

6. Conclusion

Electric vehicles are the only alternative for clean, efficient and environmentally friendly urban transport system. Switched reluctance motor drives emerge as one of the best candidates for powering the drive train of electric cars, mainly due to their high efficiency, extended power region, ruggedness and low foreseen manufacturing costs. Some switched reluctance drive design guidelines including motor sizing, power converter and control have been proposed. Finally, a 75 kW, 300 V, 12/8 switched reluctance motor prototype has been designed. Simulation shows good agreement with the expected results.

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