EVS26
Los Angeles, California, May 6-9, 2012

Integration of a Folding Electric Two-wheeler Vehicle for a Future Commuting Transportation

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Abstract

The paper issues the development, building and testing of a Folding Electric Motorbike, a lightweight, low cost and all-electric two-wheeler vehicle taking full advantage on today's city infrastructure. The technology offers drivers to combine transportation methods, lowering cost, and greenhouse gas emission. The paper documents innovative studies on how the technology can be used to explode the today's transportation system and be used to bridge the gap of today's challenges and future solutions. The optimum components to be used in the small, lightweight vehicles are selected based on the technology's functional requirements. The selection of motorbike's drivetrain components is based on the latest available technology, with respect to economic viability. The technologies first two development stages are described. In the first development stage the vehicle's functional requirements are defined. This is followed by a feasibility study and a realization on technologies capabilities. The feasibility study is performed by developing, building and evaluating an alpha-prototype vehicle. The research indicate that the possibility of developing a powerful , light-weight, low cost and all-electric two-wheeler vehicle taking full advantage on today's city infrastructure is very prospective. The alpha-prototype was successfully constructed and is considered to be ready for further laboratory testing and test driving before continuations on a fully designed beta-prototype.

Keywords: City traffic, Infrastructure, BEV (battery electric vehicle), Motorcycle, Powertrain.

1 Introduction

Today's problems regarding energy sufficiency, energy efficiency, oil independency and the environment for the transportation sector are some of the major challenges needed to be faced before achieving sustainability within the transportation sector. The average energy consumption of the transport sector in UNECE member countries accounted for 26.3% share of the total final energy consumption in 2004, the majority of this energy share was consumed by road vehicles. Moreover, the annual energy growth rate of the transport sector from 1980 to 2003 was approximately 2.9% corresponding to a 24 year doubling time [1, 2]. The increasing fuel consumption of the transportation sector has led to forecasts of oil shortages and continued price rises, which eventually will lead to the unsustainability of transportation in society.

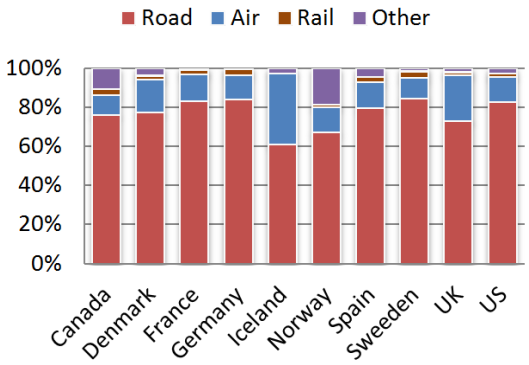

Figure 1: Consumption of energy in the transport sector, 2004.

For that reason it is considered essential to accelerate the introduction of the Electric Vehicles (EVs) into the private transportation sector. Organizations, like Better Place, have introduced attractive business models which make it more economically viable for the user to buy and operate an EV. Such models require changes on the city's infrastructure, and are not expected to be fully operational within the next years.
The personal vehicle has proofed to be capable of being trendy. Big, costly and risky steps have been taken by larger developers on developing a large four-wheeler EV. The fleet has though not yet taken any similar big steps into the new electric technology age as the communication technology has recently done. The personal vehicle will though most likely take a similar step as personal phones already have.
A new approach to vehicle functionality and usage is therefore needed for the upcoming generation.
Several different folding electric motorbikes have been developed over the last years. Most of them never reached production stage as little interest seems to be in the low power, short range and high cost vehicle.
A light weight folding vehicle is though still considered to be a viable market solution. Such product is considered to have a better chance on gaining larger market share today due to the latest technological developments.
This paper issues the first two development stages of a high power Folding Electric Motorbike (FEM), a light-weight, low cost and all-electric two-wheeler vehicle taking full advantage on today's city infrastructure. The technology is aimed to offer drivers to combine transportation methods, lowering cost, energy usage, and greenhouse gas emission.
Furthermore, the paper documents innovative studies on how the technology can be used to explode the today's transportation system and be used to bridge the gap of today's challenges and future solutions.

2 Functional requirements

In the first developing stage the problem of today's transportation infrastructure must be realized, in continuance the products functional requirements are formed.
The FEM design is aimed to be a highly reliable, high power, light weight and energy efficient EV that can be implemented into, and take full advantage of today's cities transportation infrastructure. The vehicle shall meet young drivers' expectations to a smart, flexible and powerful two-wheeler. Additionally, the goal of the designed is to accelerate the introduction of EV's on the general market and to build up a strong consumer bases. The need for charging the vehicle will be learned as a daily behaviour like charging the mobile phone or laptop computer. Accelerating the introduction of EVs is one way of leading the modern society towards sustainability.
The folding mechanism makes the high power vehicle take less storage place; furthermore, the bike fits comfortably into the trunk of a car, and can easily be carried onto buses or trains. Indeed, the design of the FEM is aimed at taking full advantage of today's transportation infrastructure. By combining transportation methods the driver can cover longer travelling distance, and easily reach the destination in congested areas in a faster and flexible way.
By such analysis the FEMs technical functional requirements are formed:

Top speed:	No less than 45km/h
Acceleration:	At least higher than the original R7 moped, must feel quick and powerful when driving.
Reliability:	The vehicle must be reliable at all times; all components must ensure reliable operation.
Range:	20 to 30 km. (12 to 20 miles)
Weight:	Light weight preferably portable.
Compact:	The vehicle shall overall be compactly designed.
Hill-climb gr.:	7°
Efficiency:	Overall high efficiency, from battery charging to tractive power.
Robustness:	Capable of operating in wet weather conditions and in the environment of modern traffic system.
Cost:	Economically viable for young drivers.
Voltage	For safety and simplification the nominal operating voltage level shall not exceed 60 V ripple-free DC[1].

[1]Danish regulations, Stærkstrømsbekendtgørelsen afsnit 6, §411.1.4.3 states that if the nominal voltage does not exceed 25 V AC (effective value) or 60 V ripple-free DC, protection against direct contact is in general unnecessary.

3 Feasibility Study

The feasibility study is the second development stage and is performed by optimisation, building and evaluation of the alpha-prototype vehicle.
The alpha-prototype is a conversion vehicle based on the ICE R7 Di Blasi. The alpha-prototype is used to validate the motorbikes, particularly its powertrain, functional performance, and to realize if functional requirements are met.

3.1 Components selection

Fig. 2 displays a block diagram of the system's components and their interactions. The vehicle's drivetrain components, energy storage system and control are displayed within the dashed box, and are the main focus point of this project.

3.1.1 Mechanical Transmission

The motor's kinetic energy must be transferred to the FEMs wheel. To transfer the power a mechanical transmission (trm) is needed. Common methods to transfer power from one shaft to another are by using belt- or chain-trm. A chain-trm weighs more than a rubber belt-trm; it is noisier and needs lubrication. The efficiency is though normally higher in chain-trm, or up to 99% [3]. The latest flat profile belt-trms are tough also high efficient, therefore it is considered better suited to use a belt trm for the FEM.
Four belts were evaluated based on the studies documented in [3], V-belts, flat belts, poly V-belts and toothed belts. The V-belt was found to be the least efficient out of the four. The flat belts are more efficient than the V-belts but put more stress on the motors bearings and is width, taking more space. The poly V-belt combines the advantages of V-belt and flat belt; however, disadvantages of the two belt types are also combined. The poly V-belt puts most stress on the motors bearings and is not as efficient as the flat belt.
The belt type considered to be best suited for the applications is the toothed belt. The toothed belt does not need to be greatly tensioned, as it does not rely on friction to transfer power, resulting in less stress on motors bearings. It has the greatest efficiency of the four belts, discussed here above, and can be used efficiently with smaller pulleys than V-belts.
For simplified, reliable and efficient design the trm shall be a two-pulley system, where the trm ratio G is defined by:

$$G = \frac{\omega_m \cdot r_{tyre} \cdot 2\pi}{60 \cdot v} \quad (1)$$

and

$$G = \prod_{i=1}^{n} \left(\frac{r_{i+1}}{r_i} \right) \quad (2)$$

where $n+1$ is the number of pulleys with the radius r, r_{tyre} is the tyres outer diameter in m, v is the vehicles speed in m/s, and ω_m is the rotor's maximum angular velocity.

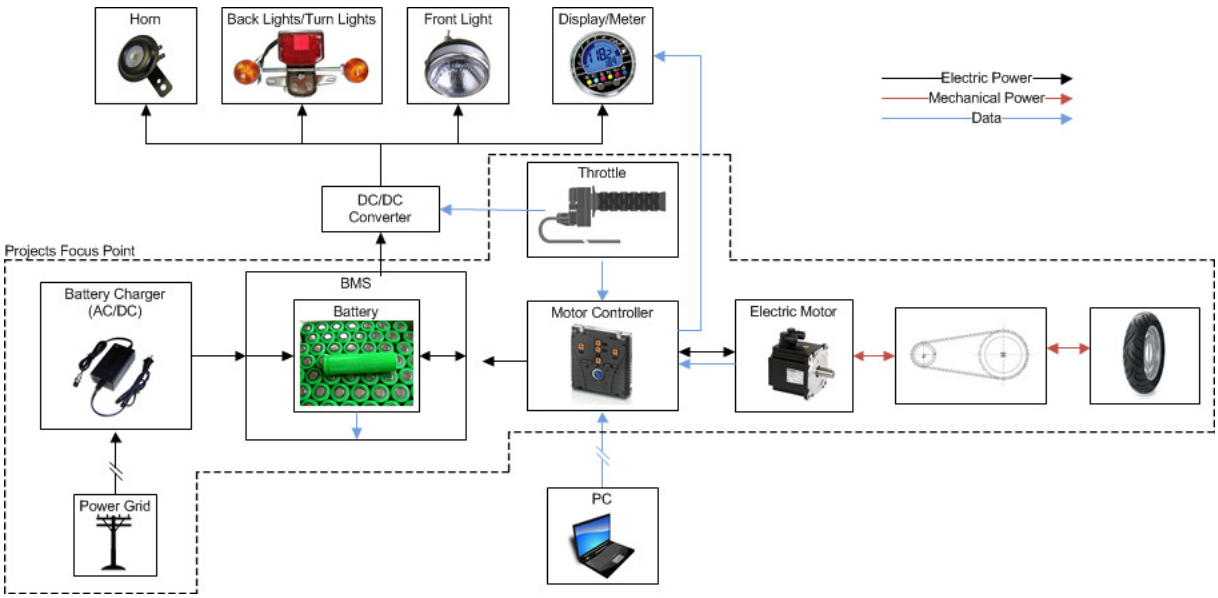

Figure 2: Block diagram of the FEM electrical system

3.1.2 Electric motor

The optimal motor for this project has to be capable of providing enough power to the wheel at high efficiency, be within reasonable cost, be light, reliable, robust, and have a fitting torque-speed characteristic. For wider selection, the trm system can be used to manipulate the delivered torque-speed characteristics. For a two pulley system, such manipulation is however limited by wheel size and motor height from ground.
The R7 combustion engine has a maximum torque of $2.56\,Nm$ and a maximum power of $0.86\,kW$. The focus will be on electric motors that are capable of delivering similar, but no less torque and power.
The evaluation included:

- Brushed permanent magnet DC motor
- Series wound field DC motors
- Shunt wound field DC motors
- Separately excited wound field DC motors
- Brushless permanent magnet motors, BLDC.

Also, the evaluation takes a close look at the advantages of various forms and constructions of electric motors, i.e.:

- Conventional motors
- Axial field motors
- Outer rotor motors and
- Wheel hub motors.

The wound field motors (series, shunt and separately excited) were not found to be suitable as they did not fulfil the project's requirements. The ones capable of delivering required power were considered to be physically too large. The shunt motors are especially undesirable due to their low starting torque and difficult control in terms of speed variation, due to their stable speed operation.
Permanent magnet motors were considered to be better suited with a view to requirements. Furthermore, due to losses in brushes, the BLDC motor was found to be the optimal choice for the application out of the five considered. In general, the BLDC motor was found to be less space-consuming and had lower weight (higher power density) than other motor types reviewed.
Three motor types, brushed DC, series and BLDC motor were further compared to realize the cost and power density difference. In the comparison, information on 37 motors was obtained. The 37 motors compared were all traction motors, some of them are widely used as traction motors in EVs. The motors ranged from $500\,W$ up to $21.5\,kW$, costing from $90\,USD$ to $1600\,USD$.
The results from the motor cost comparison is displayed in Fig. 3. The red, blue and green lines represent the fitted average value of the motors cost of variably rated power. The comparison lead to the conclusion that the BLDC motors are generally a more costly solution, and the series motor is the least costly of the three motor types compared. The brushed and BLDC motors use higher cost material, permanent magnets, to form the motors magnetic field. Series motor do not contain magnets, as the magnetic field is produced by the field windings. The magnets are considered to be the main cause of the cost difference between magnet motors and wounded motors.

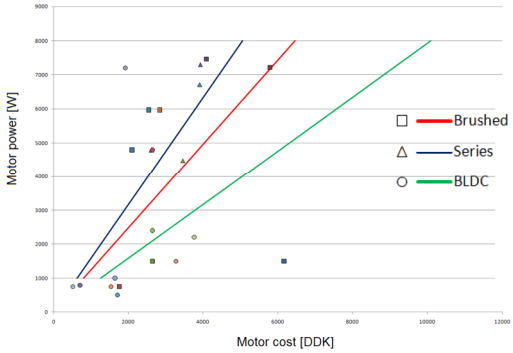

Figure 3: Cost comparison of brushed DC, series and BLDC motors, where the red, blue and green lines represent the average fitted value.

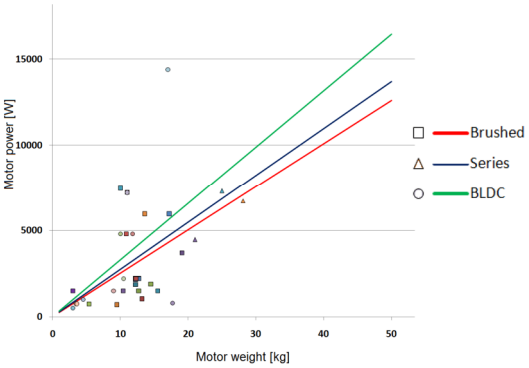

Figure 4: Weight comparison of brushed DC, series and BLDC motors, where the red, blue and green lines represent the average fitted value.

One of the functional requirements is an overall compact design, it is therefore essential to select a low weight motor. Using the data collected for the 37 motors comparison was made for the motors

weight, see Fig. 4. As previously, three lines have been fitted that represent the average value of each motor's type. The results from the comparison lead to the conclusion that BLDC motors are generally less weight than the brushed and series motors. The brushed motor is however the motor weighing the most of the three motors.
The results from motor comparisons are in consistence with other similar studied. One such is the by R.M. Cuenca, L.L. Gaines, and A.D. Vyas on EV's production and operation cost [4]. Their approach is somewhat different, thus the results yield similar results. Series motors are approx. 16% more space consuming than BLDC motors and weight approximately 60% more. The BLDC is though about 18% more costly. The 18% more cost of BLDC motors is considered to be acceptable when space and weight trade-offs are compared, making the BLDC motor the preferred selection for the FEM.
It was considered to use a non-conventional motor. Using an outer rotor in-wheel hub motor was considered to be best suited for an EV application of this kind, as it results in more simpler and compact design. The in-wheel motor is however limited by the wheels size. This is not preferable at this stage of design due to flexibility required in further design stages. The in-wheel hub motor might very well be reconsidered in a further design stage.
Other motors considered were axial field motors. Such motors are very power dense motors due to the unique compact design. Due to the complex manufacturing process, the axial field motors had limited commercial applications. In recent years, as the manufacturing process became simpler, the price became viable for the commercial market and the demand for axial field motors increases. Today the motors are widely being used in electric vehicles such as solar power vehicles [4], bicycles [5], and most recently, as in-wheel drives of larger EVs [7, 8, 9].
K. Sitapati and R. Krishnan made a comparison study on $0.25\,kW$ to $10\,kW$ axial and radial BLDC motor topologies [10]. For the same amount of active materials, the axial field motors have larger diameters than radial field motors. Their profile is flat, that is, a short axial space. Therefore the axial flux motors are better suited for limited width requirements.
The rotor of the radial field machine has in general a larger moment of inertia than the rotor of an axial field machine, due to the difference in rotor shape. The low moment of inertia enables more rapid acceleration.
Dual-gap slotted axial machines have field windings (or PMs) on both sides of the armature, or reversed. Due to the two field windings sides (or armature sides for reverse design) the back-emf is generated on both sides. This reduces the required winding turns and thereby the amount of copper used, and therefore copper losses.
By this analysis the axial field DC motor is considered to be better suited for the application and requirements of the FEM.
The motor found to be closest to fulfilling all the functional requirements was the LEM-130-95S motor from L.M.C. stationed in the UK's. The LEM-130 is a high efficient double-gap axial field brushed PM DC motor. It has been used in numbers of different EV applications [11, 12, 13] and has proven to be robust and reliable.
The LEM-130 motor is a very power dense design where power to weight ratio is $1.007\,kW/kg$. The motor is highly efficient, with rated efficiency of 87% by manufacture. It can deliver up to $6.31\,Nm$ torque at peak current of $I_p = 100\,A$, and torque of $4.35\,Nm$ at rated current of $I_m = 75\,A$. Furthermore, it is rated $3.04\,kW$ at speed of $6624\,rpm$ and $48\,VDC$, nominal voltage.

3.1.3 Motor controller

For flexible motor operation during testing and development a programmable controller is required. The controller shall also be high efficient and reliable. It must be selected with respect to the battery and motors rated values.
The PMT425S controller from PG Drives Technology was recommended to be used by L.M.C., the manufacture of the LEM-130 motor. The manufacture claimed the controller had been used with the LEM-130 motor, resulting in reliable and satisfying results.
The controller is rated for a nominal input voltage of $24\,VDC$ to $48\,VDC$, $80\,A$ in continuous operation, and $250\,A$ for $20\,s$ operation.
The manufacture claims high efficiency and minimal switching losses. It features short- and open-circuit contactor detection, throttle mapping, and electromagnetic breaking control (optional regenerative breaking system) which is proportional to the accelerators position.
The controller is designed for use in the harsh environment of EVs, equipped with insulated metal substrate (IMS) technology, offering better cooling than classical circuit boards, and a large heat sink covering one side of the device. The

operating temperature is rated from $-30°C$ to $40°C$, and is vibration protected, impact protected and insulation rating is IP54.
The controller was found to be a suitable selection for the alpha-prototype as it fulfils the projects functional requirements, and is equipped with CAN protocol that enables communications via other devices by the industry standard.

3.1.4 Electrical energy storage system

When considering electric energy storage systems that are capable of fulfilling the vehicle's functional requirements several factors must be considered. This includes; specific energy, specific power, cost, environmental considerations and safety. All are important factors when considering the choice of a portable energy storage system for the FEM.
As the projects functional requirements state, the nominal voltage of the battery shall not exceed $60\,V$. It shall though be selected closely to $60\,V$ as lover voltages result in higher system losses. Furthermore, it shall be small enough to enable the capability of delivering sufficient power to the motor.
The module shall preferably be capable of delivering more than $10\,Ah$ for obtaining a considerable driving range, and be less than $10\,kg$ for the light weight design.
Out of today's mass manufactured batteries the Li-Ion cell technology is the only electrical energy storage that is considered capable of fulfilling the projects requirements. Li-Ion cell technology has been more frequently used in EV applications over the last years and has proven to be reliable and safe when used with the latest BMS control system and voltage equalizer.
Over the last several years increased numbers of companies have begun developing Li-Ion cells and modules. The largest part of battery cell developing and manufacturing is stationed in Asia. However, due to increasing market demand on smaller Li-Ion modules, smaller companies outside Asia have started developing Li-Ion modules. One such is ACTEC A/S, stationed in Randers, Denmark.
ACTEC A/C agreed to deliver a high capacitive battery module still being developed by the company. The module is rated $54\,VDC$, $20\,Ah$, weighing only $9\,kg$ and capable of delivering $50\,A$ continuous current. The module contains the CGR-18650CH high energy dense Li-Ion cells from Panasonic. This makes a very dense and compact module design, with a specific energy of $120\,Wh/kg$, and capable of delivering $2.7\,kW$ at nominal voltage.
Though the module's rated continuous discharge current is $50\,A$, the serial connected cells are capable of delivering over $90\,A$ in continuous operation at $20°C$. The current limit is due to the terminals, connectors and protection circuit inside the battery as it was original developed for less powerful cells.
Although the module is not able to deliver the required current for taking full advantage of the motor's capabilities, the module makes up by its high specific power. Therefore it is considered to be well suited for the FEM.

3.2 Modelling vehicles performance

To ensure the motor fulfils requirements regarding acceleration and top speed, the vehicle performances are modelled by mathematical physics and analytical expressions. Thereafter calculations and dynamic simulations are done based in the information provided by the manufacturer. The method applied is according to the method introduced in [14].
First a suitable gear ratio is determined for a top speed of approx. $45\,km/h$. The relations of motor's and vehicle's speed are described by Eq. 1. By inserting the following values:

$\omega_m = 7000\,rpm$
$r_{tyre} = 0.155\,m$
$v = 12.5\,m/s$

a gear ratio of $G = 9.1$ is found.
After determining a reasonable gear ratio for the vehicle, the motor's acceleration capabilities are considered. The motor shall be capable of accelerating the FEM up to a top speed of approx. 45km/h within a reasonable time. When the FEM is in equilibrium in an inertial form of reference the vector sum of all forces acting upon the FEM must be zero. Furthermore, according to Newton's first law of motion, a body acted on by zero net forces moves with constant velocity and zero acceleration. By this the following is true for non-accelerating object:

$$\sum \vec{F} = 0 \qquad (3)$$

Where $\sum \vec{F} = 0$ is the sum of all force vectors acting on the object. By implementing the major forces action on the FEM, Eq. 4 is obtained:

$$F_{te} = F_{ad} + F_{rr} + F_{hc} + F_{la} + F_{\omega a} \qquad (4)$$

where the forces are as follows; F_{te} for tractive effort, F_{ad} for air drag, F_{rr} for rolling resistance, F_{hc} for hill climbing F_{la} for linear acceleration and $F_{\omega a}$ for angular acceleration. It shall be noted that at constant speed the force of linear and angular acceleration are zero. For this Eq. 4 can be rewritten as:

$$F_{te} = K_a \cdot v^2 + m_l \cdot g \cdot (\mu_{rr} \cdot \cos(\alpha) + \sin(\alpha)) \quad (5)$$

where v is the vehicles speed, m_l is the laden weight, g is the acceleration due to gravity, μ_{rr} is the tyres rolling resistance, α is the roads angle, and K_a is the frontal air drag constant:

$$K_a = \frac{1}{2} \cdot \rho_{air} \cdot A \cdot C_d \quad (6)$$

where ρ_{air} is the air density, A is the vehicle's frontal area and C_d is the drag coefficient.
The left-hand side of Eq. 5 can be described as a function of the motors torque τ_{em}:

$$F_{te} = \tau_{em} \cdot \frac{G}{r_{tyre}} \cdot \eta_G \quad (7)$$

where η_g is the transmissions efficiency.
The motor's torque depends on rotor's speed:

$$\tau_{em} = \frac{K_m\phi \cdot v_a}{R_a} - \frac{(K_m\phi)^2}{R_a} \cdot \omega_m \quad (8)$$

where $K_m\phi$ is the the torque constant, v_a is the armature voltage and R_a is the armature's resistance. Eq. 8 only applies within the interval $\omega(\tau_{em,max}) \leq \omega(\tau_{em}) \leq \omega_{max}$ as the armature current is limited[2]. The motor's rated maximum torque is defined in the manufacture's motor's data sheet, [15]. Now, the two intervals can be defined:

$$\tau_{em} = 4.35\ Nm, \quad for\ \omega_m = \left]0\ \frac{rad}{s}, 725.19\ \frac{rad}{s}\right[$$

$$\tau_{em} = 93.19 - 0.123\ \omega_m, \quad for\ \omega_m = \left]725.19\ \frac{rad}{s}, 760.70\ \frac{rad}{s}\right[$$

By using Eq. 1, 7 and 8 the FEM's tractive effort at any given vehicle speed can be found. Fig. 5 displays a plot of the tractive effort over variable vehicle speed among the net forces acting on the vehicle. According to the calculations the vehicle shall be capable of maintaining a speed of approx. $12\ m/s$ when climbing $\alpha = 10°$.

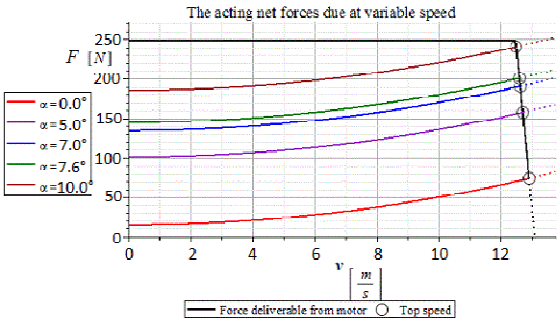

Figure 5: LEM-130-95S motor. FEM's driving characteristics at full throttle and variable hill climbing angle, force over speed.

For realizing the acceleration characteristics of the FEM using the LEM-130 motor a dynamic simulation is performed. The simulation is based on the same principles as before, adding the force of linear and angular acceleration:

$$F_{la} = m_l \cdot a \quad (9)$$

$$F_{\omega a} = J \cdot G^2 \cdot a \quad (10)$$

where a is the vehicles acceleration defined as $\frac{dv}{dt}$, and J is the rotor´s inertia. The vehicle´s velocity over time in time intervals of $\Delta t = 0.1s$ was plotted using MATLAB. The results are diaplayed in Fig. 6.

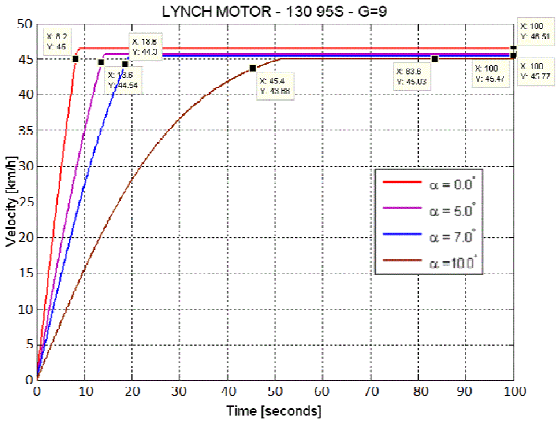

Figure 6: LEM-130-95S motor. FEM's driving characteristics at full throttle and variable hill climbing angle, speed over time.

The markers to the far right display the top speed of each slope degree, while the markers to the left display the time it takes the moped to reach 97% of

[2] If the current would not be limited the motor would overheat. The current is limited by the controller and backed up by the BMS.

its top speed. It is not until at 10° slope the motor shows signs of struggling to reach top speed, where it takes it about 45.4 s to reach 97% of the top speed. It is also interesting to note how rapidly the vehicle stops accelerating. The vehicle accelerates up to about 45 km/h very rapidly, but then this acceleration suddenly ceases. This sudden decrease of acceleration is due to the motor's torque-speed characteristics. The motor delivers a constant torque to the vehicle's tyre until a critical speed is reached. At the critical speed the back emf begins to affect the delivered torque.

Fig. 7 shows how long time it takes the vehicle to drive an approximate distance of 50 metres at variable slope angles. First, the non-slope angle, marked with a red line, the vehicle takes only 12.0 s to cover 50 m on a level surface and just over 22 s to climb up 50 $m$etres at 10° slope.

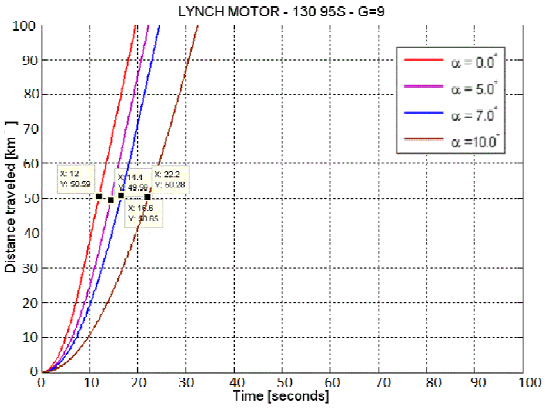

Figure 7: LEM-130-95S motor. FEM's driving characteristics at full throttle and variable hill climbing angle, distance over time.

Table1 is provided to sum up the motor's capabilities. The LEM-130-95S does, in some way, exceed expectations; it considered to fulfil the requirements.

Table1: Motor specifications and simulation results.

$G = 9$	
$\alpha_{max} = 13.75°$	
$F_{te,\,to} = 247.53\ N$	
$P_{em} = 3.02\ kW$	
Weight $= 3\ kg$	
$\eta_{peak} = 87\%$	
$\mathcal{J} = 117 kgm^2$	

α	ν_{max} [km/h]	$\nu_{97\%}$ [sec]	50 m [sec]
0.0°	46.51	8.2	12.0
5.0°	45.77	13.6	14.4
7.0°	45.47	18.6	16.6
10.0°	45.03	45.4	22.2

3.3 Vehicle testing and evaluation

After all the electric components had been fitted on the frame and connected, the system was powered up and tested, see Fig. 8.

The motor controller needed to be adjusted with regards to the Hall effect handlebar's output voltage.

Further measurements and testing were done using the Hall effect accelerator. The FEM's rear wheel was lifted up as displayed in Fig. 8, and the back tyre allowed rotating without any applied load, except windage. The R7 moped was equipped with a speedometer, and calibrated using a digital tachometer.

Voltage and current measurements on the vehicle's electrical interface components, controller and motor were taken. A 100 A fuse was installed on the motor controller's positive power terminal for system protection. The voltage drop over the fuse was measured 1.0 mV. Due to this low voltage drop, the motor controller's voltage is assumed to be equal to battery voltage at steady state. The battery current equals the sum of current to the control circuit and motor controller.

All current probes used were Hall effect sensors and gave a measuring signal of 1mV/1A. Before taking any measurement the probes were calibrated.

Figure 8: The assembled vehicle ready for testing.

Table 2 displays results of system voltage and current measurement. The measurements were taken at a stable speed.

The results yield the system's efficiency, from battery output to power delivered to the motor. The measurements were taken for different wheel speeds, ranging from 5 km/h to 62 km/h.

Table2: System measurements under no-load.

Speed	11 km/h			
Voltage [V]	62.6	62.6	10.61	62.6
Current [A]	2.91	2.4	7.2	0.51
Power [W]	182.166	150.24	76.39	31.93
Efficiency	Over all: 41.93% - Controller: 50.85%			
Speed	18 km/h			
Voltage [V]	62.33	62.33	16.95	62.33
Current [A]	4.711	4.2	7.8	0.51
Power [W]	293.64	261.79	132.21	31.79
Efficiency	Over all: 45.04% - Controller: 50.50%			
Speed	29 km/h			
Voltage [V]	61.96	61.96	27.10	61.96
Current [A]	7.207	6.7	8.5	0.51
Power [W]	446.55	415.132	230.35	31.60
Efficiency	Over all: 51.59% - Controller: 55.49%			
Speed	53 km/h			
Voltage [V]	61.41	61.41	49.28	61.41
Current [A]	10.49	10.0	11.2	0.493
Power [W]	644.19	614.10	551.94	30.28
Efficiency	Over all: 85.68% - Controller: 89.88%			
Speed	62 km/h			
Voltage [V]	61.12	61.12	57.37	61.12
Current [A]	11.47	11.2	12.4	0.486
Power [W]	701.05	684.54	636.99	29.70
Efficiency	Over all: 90.09% - Controller: 93.07%			

It is interesting to note how the controller's efficiency is relatively low at low speed, yet high at high speed. The converter's efficiency is dependent on the operating duty-cycle. Each topology has its own efficiency to duty-cycle characteristics.

The system's interface power dissipation is relatively stable over variable speeds. The interface is dissipating approx. 30 W which is about 0.81% of what the battery can deliver fully charged ($62\,V \cdot 60\,A = 3.74\,kW$).

At full throttle, the free-wheel speed was measured $62\,km/h$. It is thus expected that the driving speed will be somewhat less due to the applied load of air drag and tyre rolling resistance. The power delivered to the motor while turning the wheel at $5\,km/h$ and $63\,km/h$ is approx. $38\,W$ and $637\,W$, respectively. The difference can be the results of motor's efficiency characteristic, and windage due to rotating components. At low speed the windage has less effect, the $38\,W$ are therefore mainly due to electrical and mechanical losses. At high speed, the force needed to overcome windage becomes larger. To obtain lower windage losses, different tyres, rims, and transmission system should be considered.

It was not possible at this stage to measure the system under loaded conditions. In such measurements the motor efficiency can be mapped, as other components under variable loads. The measurement results provided here are to give a general idea of the system's behaviour. The maximum efficiency found for the overall system that is from power delivered from battery to the power delivered to the motor was 90.9%, where the controller efficiency was 93.1%. The motor's peak efficiency is 87%, the system is therefore considered to be high efficient. In order to obtain the efficiency from power source to vehicle's mechanical output, the battery's charging to discharging efficiency should also be taken into account in further measurements.

A short outdoor test was performed on the vehicle. The top speed on a relatively flat surface was measured $53\,km/h$ with a fully charged battery. The top speed dropped after approx. $5\,km$ to $50\,km/h$ as battery voltage decreased.

When pulling the throttle to its maximum, the battery's BMS switches the module momentarily off. This was expected as the motor is capable of drawing a higher current than the battery can deliver. Reprogramming the motor controller for limiting the current drawn from the battery was therefore done. This does not occur when accelerating less rapidly, as less torque is produced by the motor, and less current is drawn from the battery. Pulling the throttle to its maximum at standstill is thus not recommenced as the front wheel will start to lift off from the road surface, that is, if the battery would not shut down.

Several runs over distances were timed, that is 10, 20, 40 and 60 metres. The measurements where done by measuring covered distances and time using a handheld timer. This test is not completely accurate, as human error must be taken into account. The measurements obtained, however, gave a reasonable idea of the vehicle's capabilities and are comparable to earlier similar measurements.

Fig. 9 displays the results from the test driving, marked with a black line. At $40\,m$ and $60\,m$ the vehicle's speed was measured 40 km/h and 48 km/h respectively.

Also on the graph are earlier measurements, done prior to the conversion process, that is, on the original ICE R7 moped, indicated by a grey line.

For the first ten metres, the difference between the two vehicles is not particularly great, both covering the distance in about 3 sec. After 10 metres the electric motor seems to rapidly accelerate. The FEM covers the $60\,m$ on $7.79\,s$ compared to the R7 covering $60\,m$ on $9.33\,s$. The FEM reaches nearly top speed in 8 sec., or 60 m.

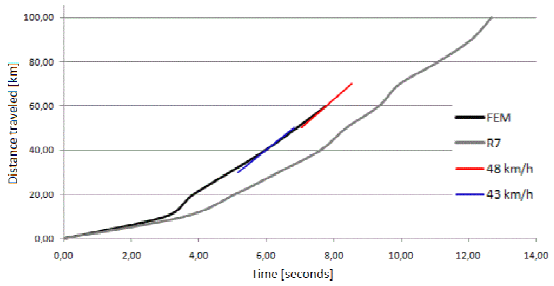

Figure 9: The vehicle test driving results.

The results are in consistence with the simulated values and are considered to fulfil the applications requirements.

4 Realization on the technology's capabilities

The FEM is a powerful lightweight electric motorbike capable of 45km/h, fast acceleration, and minimum driving range of 30km. With the folding mechanism, the bike fits comfortably into the trunk of a car, and can be carried onto buses or trains.

The FEM is a small, lightweight vehicle that can be used as a standalone vehicle or as a supplementary transport medium integrated with public transportation. As a result, the technology of the motorbike can potentially generate new and desirable opportunities in modern urban and inner city transportation.

The results presented in this paper indicate the vehicle can be made economically viable for the consumer. The pricing of a mass produced vehicle is expected to be within the range 2000 USD to 6000 USD. The price difference depends on the components pricing development, frame design and interface.

As modern cities grow and become more densely populated, vulnerability of transportation infrastructure increases, and they often become overloaded due to the large space demanded by the personal car. This is a well-known problem in Europe's most populated cities. Moreover, the average travel distance from home to the work place is greater in larger cities, leading to more personal transportation energy consumption and greater emission of greenhouse gasses.

The small, lightweight electric motorbike can be implemented into the existing city infrastructure, and thus offers an alternative option in terms of personal transportation for the growing modern cities. The motorbike is designed to fit comfortably in the storage room of a train, as well as into the average car trunk. These factors render the motorbike as an attractive transportation option within urban areas. The primary target group which would find this option most appealing is deemed to be urban individuals between 17 and 40 years of age, either residing in inner city areas or more suburban areas. An important factor is the resulting exposure and familiarization with a low-cost, electrically powered motorbike which can be easily manoeuvred and which provides an energy-sufficient and comfortable commute between the home and the workplace. That in turn has the potential of resulting in increased awareness of electric vehicle (EV) technology, which could lead to a paradigm shift in how personal transportation is regarded, not just in terms of individual needs, but in terms of the much bigger scope of international environmental energy sufficiency and awareness.

The FEM has all the potential of being the technology that introduces EV technology to young and upcoming drivers. It can easily be argued that drivers who have a positive experience of the EV technology are more likely to invest in another EV. Buying a FEM is financially a markedly less substantial commitment than the purchase of full-size electric car. It is therefore our opinion that the FEM is a technology that can help the market shift towards being fully able to receive the electric car.

5 Further work

Further works involve further developments, building and testing a beta-prototype in a co-operation with a partner. The beta-prototype's frame design is in process, and is aimed to be folding, compact and light weight.

6 Conclusion

The powertrain of the vehicle alpha-prototype has been assembled and is ready for further validation analysis. All components were selected after a thorough evaluation process and with respect to the technologies functional requirements.

The findings of this paper indicate that axial flux PM machines are the most suitable solution for vehicle tractive applications where low weight, compactness and high power is required. Using such a machine is however, not the most economically viable solution, due to the complex assembling method currently in use by manufacturer. The motor speed is controlled by a flux-vector, CAN protocol interface module. The

CAN communication protocol interface allows redefinitions and modifications to all control parameters, which is a valuable tool in further development.
Already existing technology is not considered able to meet all the specific requirements of the unique FEM.
The system's battery module is equipped with relatively new battery cell technology that results in high energy density and high current output capability. However, the battery module is the heaviest component on the FEM. Reducing the module's size affects its output current capabilities, or output voltage level. This eventually results in a reduction of the vehicle's driving range, weight and power.
The powertrain is a high power design, and capable of a long driving range. The weight must however be reduced to enable easier portability when folded. The vehicle's weight can be reduced by a lighter frame design which meets the vehicle requirements.
The research indicate that the possibility of developing a powerful , light-weight, low cost and all-electric two-wheeler vehicle taking full advantage on today's city infrastructure is very prospective.

Acknowledgments

Joachim Hjerl, David Koch Mouritzen and Christian Rottbøll at CityRiders are thanked for bringing the project to DTU, providing the authors with the opportunity for undertaking this project. Special thanks to Verkís for all their support while writing the paper and presenting this paper. Landsvirkjun is thanked for funding and believing in the project. Thanks to all the staff at DTU's CET department for the help and support. Finally, thanks to the author's family for the understanding and moral support during all the long working days during the project.

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