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DESIGN AND IMPLEMENTATION OF AN ELECTRIC POWERTRAIN FOR THE KIIRA ELECTRIC VEHICLE

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Abstract

Research in greener transportation technologies has become increasingly obtrusive worldwide and Electric Cars are at the forefront. In line with this, Makerere University embarked on designing an Electric Car as a proof of concept. The concept car was named KIIRA Electric Vehicle (KEV) and is the first Electric Car to be designed in Uganda. The design of the powertrain for KEV was undertaken following a guided engineering process starting with requirements engineering for the car. A design process which involved calculations for the required motor torque, horsepower and energy capacity of the battery pack was undertaken using approved formulae and there after specifications were made. The major components were the AC Motor and Controller, DC-DC converter, Battery pack and the Battery Management System. All the modular systems were configured using the manufacturer's software and integrated into a functional electric powertrain for KEV utilizing some of the firmware developed by the KEV team. The electrical systems' architecture was made to suit the local requirements using the University campus as a test and development ground. The low voltage (12 V) electronics were also designed to source power from two linked power sources.

Key Words: *Electric Car, KIIRA Electric Vehicle, Powertrain*

1. Introduction

KIIRA Electric Vehicle (KEV) is a "proof-of-concept" car, designed at Makerere University, Uganda, to demonstrate the passion, capability and discipline within our young engineers to address contemporary issues related to climate-change and to stir up research in greener transportation technologies. The name "KIIRA" is the Ugandan version of the name of the World's longest river – the Nile, which is the source of virtually all the hydro electricity in Uganda and is expected to supply the charging power for the car.

KEV was conceptualized against the background that to curb down the levels of emissions from man's activities which history shows have had dramatic consequences in nature, green transportation must be promoted and prioritized [1]. The uniqueness of KEV lies in its Powertrain, as is characteristic of all Electric Cars. KEV's unique electrical Systems' architecture incorporates the unique requirements established in the design process to suit the local terrain and climate of the design and test center.

KEV is an all Electric Car using batteries as the primary source of energy to run all the systems within the car. The concept of a battery electric vehicle is essentially an electric battery for energy storage, an electric Motor, and a Controller [2]. KEV is designed to be a short range, low speed commuter vehicle to suit the University campus transport requirement [3].

This paper highlights the system architecture for the entire electrical systems and the procedures undertaken in the design and implementation. It focuses on the high voltage electrical systems and their specifications. It covers the aspects for sizing of the key features of the electric Powertrain, namely, the battery pack, the Motor, and the Motor drive Controller. These aspects are detailed in the following sections. A functional Powertrain was realized after integration of the different systems specified for the customized Powertrain.

1 The Design Process

KEV's electrical systems architecture is based on the generic battery Electric Car systems' configuration [4]. Prior to concretizing the detailed system concept, a requirements engineering process for the car was undertaken. This involved carrying out case studies at the test center for the terrain, the climatic conditions and along with anthropometry studies as well. This requirement engineering process provides a foundation upon which design decisions are made.

1.1 Establishing the Requirements

Upon finalizing the pre-design surveys and studies using Makerere University campus as the focus area, a number of requirements were established. The design decisions were made basing on these established requirements. These requirements were categorized into functional and non functional. Table 1 gives the functional requirements.

Table 1: The Requirements for KEV Electrical Systems

Requirement	**Value**	**Units**
Powertrain Configuration	Battery Electric	-
Range	80	Km
maximum speed	100	Km/hr
Maximum Gradability	4	%
overall weight	≤ 1200	Kg

Among the non functional requirements considered was Safety, Reliability of the System and System Stability. In the establishment of the safety requirements, the US Federal Motor Vehicles Safety Standards (FMVSS) standards were referred to [5].

1.2 Design Specification Process

Meeting the above requirements would require a punctilious design achieved after following an engineering process. KEV's battery electric Powertrain required 3 major components which had to be sized to meet the requirements. Specifications for the sized system were made before attainment of the architectural concept of KEV.

2.2.1 The Motor

The traction for KEV was achieved through a single Motor fitted at the front of the vehicle. This configuration eliminates the use of a differential to accommodate unequal speeds of the inside and outside wheels of the rear axle during vehicle cornering thus reducing the complexity of the transmission [6]. The Motor had to be sized in terms of horsepower and torque requirements. To obtain these parameters, a number of contributing factors were considered, as it is typical in the design of any road car. These were Acceleration Force (F_a), Aerodynamic force (F_d), Climbing Force (F_h), Relative Wind Drag Force (F_w) and the Rolling resistance Force (F_r) [7]. To determine the total force, Equation 1[7] below was applied.

$$\text{Total Force} = F_a + F_h + F_r + F_d + F_w \quad (1)$$

In the equation

$$F_a = C_i * W * a$$

Where

C_i is the mass factor

W is the vehicle's weight

a is the acceleration [m/s^2]

$$F_h = mg\sin\theta$$

Where

F_h is the climbing force (N)

m is the vehicle's mass (kg)

θ is the angle of incline (degrees)

g is the acceleration due to gravity (m/s^2)

$$F_r = C_r * W * Cos\theta$$

Where

F_r is the rolling resistance force

C_r is the rolling resistance factor

$$F_d = 0.5 * \rho * C_d * A * V^2$$

ρ is the density of air

C_d is the drag coefficient of the vehicle

A is the projected area in the vehicle's direction of motion

V is the vehicle's speed

$$F_w = F_d * C_w$$

Where

F_d is the aerodynamic drag force

C_w is the relative wind factor defined by;

$$C_W = 0.98\left(\frac{w}{V}\right)^2 + 0.63\left(\frac{w}{V}\right)C_{rw} - 0.40\left(\frac{w}{V}\right)$$

Where

w is the average wind speed

V is the vehicle speed

C_{rw} is the relative wind coefficient

Conditions at Makerere University Campus were used to determine the coefficients for the aerodynamic drag, rolling resistance, and relative wind drag force. Several computations were made

Table 2: The overall efficiency of the transmission components

Drivetrain type	Manual transmission	Drive shaft	Differential drive	Drive axle	Overall efficiency
Front wheel drive	0.96	Not required	0.97	0.98	0.91

for different scenarios (on a level road and when climbing at different angles of inclination.

Considerations for the final efficiencies of the drive line were made as portrayed in Table 2. A product of the subsystems estimated efficiencies resulted in an overall efficiency of 0.91.

Upon considering the different scenarios of driving conditions, the highest power requirement was established. With the efficiency of 0.91, the overall horse power for the Motor obtained was found to be 17Hp.

2.2.1.1 Motor Specification

Distinctively two major options were available, namely, Alternating Current (AC) & Direct Current (DC) Motor types. Owing to the cost, weight and greater efficiency at full load among other attributes, an AC Motor was chosen. The AC Motor types available to choose from included, Induction, Permanent magnet and Switched Reluctance Motors. From considerations of weight, cost and efficiency, an Induction Motor was selected owing to its superiority to the other types basing on the key attributes considered. Thus the drive for the KEV was an AC Induction Motor with a single gear reduction gearbox incorporated.

Upon determination of the power rating for the Motor, the Revolutions per minute (Rpm) was another key attribute to be considered. Equation 2 was used to determine the maximum Rpm expected from the Motor.

$$\mathrm{RPM}_{\mathrm{motor}} = \frac{100}{6} * \frac{V}{2\pi * R_{WR}} * GR \qquad (2)$$

Where

V is the velocity (km/h)
R_{WR} is the wheel radius (m)
GR is the gear ratio

Using a constant gear ratio in the calculations, the maximum Rpm was approximately 1800. Thus the Motor to be used in the Powertrain had to at least hit this targeted Rpm. Based on the specifications arrived at, a Motor from Azure Dynamics Electric Drive Solutions was procured and used. The Azure AC24 was found to have a power rating close to the design specifications and possessed the required attributes for the Motor specified. The actual Specifications of the Motor are provided in Table 3.

2.2.1 Motor Controller

The AC Motor selected required an inverter since the primary energy source is a battery pack which outputs a DC voltage.

This implied that the Motor drive controller had to have two major sub components - the Inverter and the Controller as captured by a schematic in Fig. 1. An inverter utilizing fast switching Insulated Gate

Bipolar Transistors (IGBTs) was specified to meet the performance requirements.

Closed loop Control Algorithm was specified for the Controller owing to the better performance of such an algorithm. Further still, Vector control (closed loop) had to be implemented by the Controller as it is well suited for control of the type of modern three-phase power electronic converters which were to be utilized in KEV's inverter stage [8].

Table 3: Specifications for the Motor

AC 24LS Specifications		
Motor Winding Configuration		Wye @312VDC
Peak Torque	Nm	92
Continuous Torque	Nm	42@4700 rpm
Nominal Speed	rpm	4600
Maximum Speed Powered	rpm	11000
Maximum Mechanical Speed	rpm	12000
Maximum DC Current	A	165
Maximum Motor Phase Current	A	250
Continuous Shaft Power at 30°C	kW	20@4700 rpm
Peak Efficiency	%	87
Peak Shaft Power	kW	47
Weight AC24LS (Motor & Gear Box)	kg	40 +18
Minimum Recommended Nominal Battery Voltage	VDC	288
Maximum Recommended Nominal Battery Voltage	VDC	336
Maximum Operational Voltage	VDC	400
Min/Max Operating Temperatures	ºC	-40 to 55

The control for the Motor is key in the performance of the drive system. A customized control system

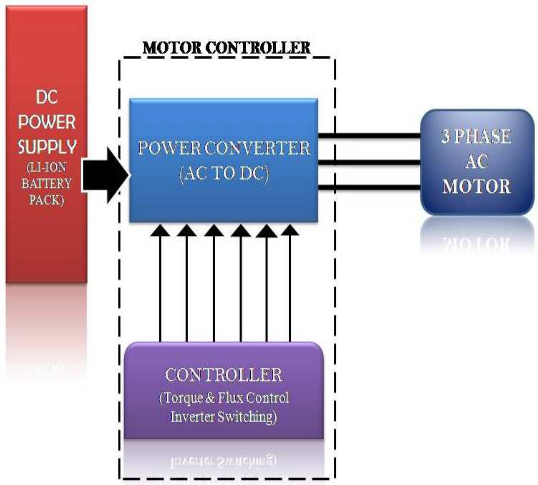

Figure 1: A Schematic of the Motor Controller

for the Motor with a smooth interface operation was established. Since the Motor supplier (Azure Dynamics) produced controllers as well, it was decided to procure the Controller from the same supplier as well. This was the DMOC445 Controller which is air cooled thus reducing on the overall weight for the system. Specifications of this Controller are provided in Table 4.

2.2.1 The Battery Pack

The battery Pack design was undertaken with consideration of three Battery chemistries only, namely, Nickel-Metal-Hydride (NiMH), lead Acid (Pb-Acid) and Lithium ion (Li-ion) batteries. A comparison of the three was performed to choose the best option. Table 5 provides this comparison.

Li-ion batteries were opted for owing to their unique attributes (specific energy and energy density) [9]. It is important to appreciate that presently Lithium-ion secondary batteries are substituting most secondary batteries currently used for traction in electric vehicles [10].

Table 4: Specifications for the Motor Controller

DMOC445 Specifications	
Weight	14.7 kg
Minimum Operational Voltage 100 VDC	Minimum Operational Voltage 100 VDC
Maximum Operational Voltage	400 VDC
Minimum Battery Voltage for Power up	120 VDC
Recommended Minimum Nominal Battery Voltage	144 VDC
Recommended Maximum Nominal Battery Voltage	336 VDC
Unit Peak Efficiency	97%
Min/Max Operating Ambient Temperature	40˚C to 55˚C
Maximum Motor Current	280A rms
Peak Power	78kW @ 312V
Continuous Power	38kW @ 312V
Max. Voltage “On Charge”	450 VDC
Minimum Auxiliary Supply Input Voltage (12V DMOC)	11 VDC
Maximum Auxiliary Supply Input Voltage (12V DMOC)	15 VDC

High performance Electric Cars have used Li-ion battery packs as exemplified in Mitsubishi iMiEV and the Tesla Roadster electric vehicle which has one of the largest and technically most advanced Li-ion battery packs in the world.[11]

The total energy requirement from the battery pack was computed, factoring in the top speed, the range and the tolerances for the Li-ion batteries. Equation 2 was used to calculate the total energy capacity of the battery pack.

$$Capacity = CR * R \quad (3)$$

Where

CR is the Consumption rate (kWh/mile)

R is the range (miles)

Using an average consumption rate of 180Wh/mile for midsized sedans [12], and the required range for the design (80km/50miles), the total energy capacity was computed.

The other considerations taken into account during sizing the pack were the Peukert Effect Constant (P_k) and the Depth of Discharge (DoD). P_k was taken to be 1.05, DoD, as a rule of thumb was taken to be 20%. These gave an overall tolerance of 1.31.

Table 5: Summary of the comparison between Pb-Acid, NiMH and Li-ion batteries

Battery type	**Pb-Acid**	**NiMH**	**Li-ion**
Nominal cell voltage	2.1	1.2-1.3	3.6
Operating temperature range ˚C	35-70	20-60	-20-60
Lifecycles To 80% DOD	500-1000	1000-2000	1200+
Specific energy (Wh/kg)	35-50	60-80	80-130
Power density W/kg	150-400	200-300	250-340
Efficiency	80	70	>95
Self discharge rate/month	3%-20%	30%	8%-30%
Estimated cost US$/KWh	100-150	200-350	200

The total energy capacity for the pack was computed as a product of the result from Equation 3 and the tolerance of 1.31. This gave a capacity of 11.7 kWh.

A series configuration for the battery pack was adopted to obtain the maximum terminal voltage of 256V.

Using Equation 4, the capacity of the battery pack (in Ampere-hours) was computed and found to be approximately 40Ah.

$$Capacity = A_p * V_t \qquad (4)$$

Where

A_p is the pack Ampere-hour rating (Ah)

V_t is the terminal voltage (V)

Thus, due to the design configuration (series connection with one parallel string), each battery cell was required to have a capacity of 40Ah.

Based on the performance requirements already established in section 1, appropriate batteries conforming to the design were selected with the terminal voltage and the total battery pack weight taken into account. Thundersky batteries (WB-LYP40AHA) were found to satisfy these design specifications, presented in Table 6.

Table 6: Specifications for the Thundersky batteries

Nominal Capacity	-	40AH
Operating voltage	Charge	4.0 V
	Discharge	2.8 V
Max Charge Current	-	<3CA
Max discharge current	Constant Charge	< 3CA
	Impulse Current	< 20CA
Weight	Tolerance ±50g	2.3 kg

For a smooth operation of the battery pack, an appropriate Battery Management System was required. The Lithiumate pro from Lithiumate BMS family of elithion was used for this purpose considering the form factor of the batteries used.

The pack was divided into eight banks, each with eight cells to ensure optimum space utilisation. The monitoring of the status of each cell was performed through a board fitted on each cell. These boards would then communicate to the BMS controller. Fig. 2 shows the assembled battery pack with, the battery management connected. Each cell has a sensor and a balance booster which communicates with the BMS controller unit, thereby reporting Voltage, Current, Temperature and State of Charge of each cell in the pack.

Figure 2: The Li-ion battery pack assembled

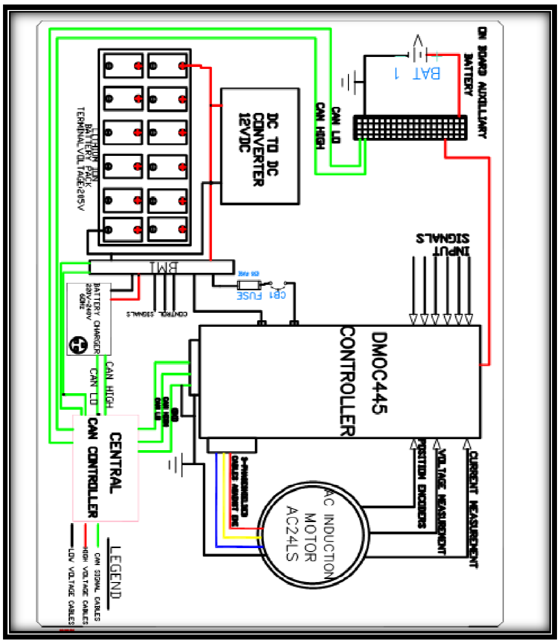

Figure 3: KEV Powertrain layout

Fig. 3 shows the overall system layout of the Powertrain. The high voltage end interfaces with the low voltage end through a DC to DC converter which works in collaboration with the auxiliary

12V battery. The Motor Controller requires this 12V present for it to start operation. The BMS is also powered by the 12V supply from the two units.

3 Results

The objective of the design process was to realise a functional Powertrain that met the targeted milestones and set design goals. The entire Powertrain was assembled on a test bench from the selected components, with tests performed thereafter.

Fig. 4 provides a 3D perspective of the subsystems of the KEV Powertrain. Following the tests on the bench for the entire Powertrain, each subsystem was reconfigured prior to mounting unto the car. Fig. 5 shows a sectional view of KEV with the assembled Powertrain mounted. To check performance, KEV was then test - driven after installation of the Powertrain, in accordance with the design.

Figure 5: Sectional CAD model of KEV with the Powertrain

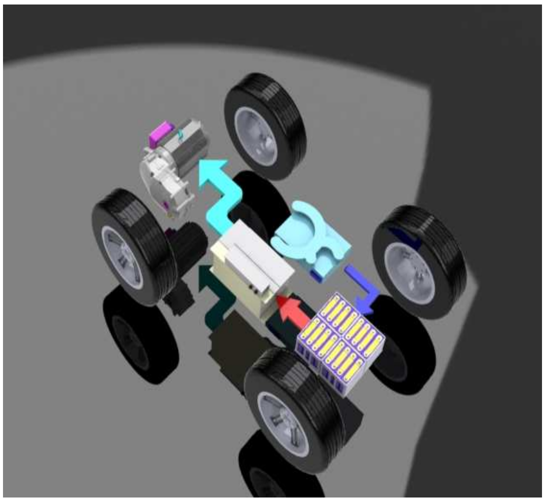

Figure 4: The Layout of the Powertrain

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