Modeling and Simulation of BLDC Motor based Propulsion System for Electric Bicycle

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Abstract - Electric Vehicles relying on electric propulsion are acquiring place in to automobile market world-wide as they attempt to merge both health and environmental benefits and are eco-friendly alternative to travel short-to-moderate distances. The idea of electric propulsion has grabbed attention from customers due to their better performance, efficiency and it's undependability on petroleum resources or fossil fuels. This paper discusses the fundamentals of propulsion for bicycle and electric propulsion system using BLDC motor powered from Li-ion battery with illustration of simulation results carried out in MATLAB/SIMULINK platform.

Index Terms— electric propulsion, Inverter, Brushless DC motor, Li-ion battery, motor controller and hall sensor.

I. INTRODUCTION

As the price of fossil fuels is rising significantly since few years and seems no turning back at lower prices, such scenarios are making one to think about electric powered vehicles. To start with such invention an electric bicycle can be a basic to understand the behaviour of electric propulsion.

The main advantages of electric bicycles are

- It does not cause air pollution, noise pollution as gasoline powered vehicles do.
- It does not require license, insurance, parking and registration fees.
- It is not bound to road network and reduces traffic issues of urban areas.
- It also reduces the cost of travel compared to gasoline powered vehicles [1][2].

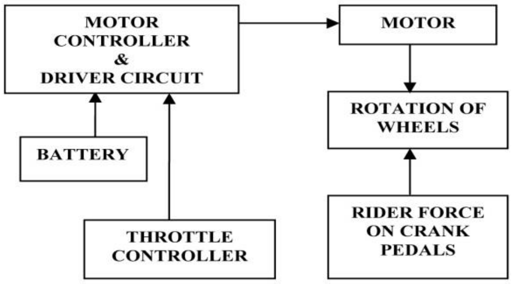

Fig .1 Block diagram of an Electric bicycle

Fig .1 illustrates necessary components to be incorporated to construct an electric bicycle. The electric propulsion system should essentially consist of an electric motor along with a power source. In this paper we have used BLDC motor for propulsion and Li-ion battery as power source. The speed of motor is varied according to rider's demand, using controller and driver circuit. The rider can input speed command through throttle whose output is given to input of motor controller and driver block. Also, drive capacity and speed range of electric bicycle can be increased if rider puts mechanical force on crank pedals by pedaling.

II. FUNDAMENTALS OF ELECTRIC PROPULSION

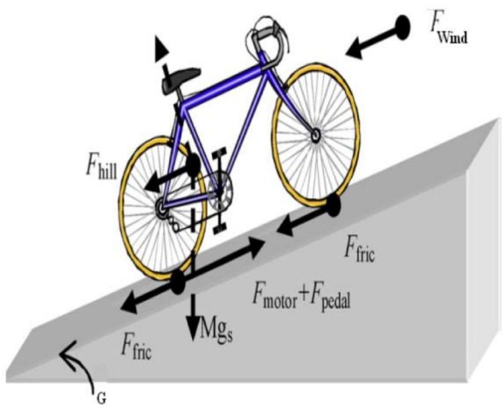

Fig .2 Mathematical model of electric bicycle

In order to describe behavior of electric propulsion, a sophisticated mathematical & mechanical knowledge is required. The power is consumed in propelling a bicycle along with rider's and also cargo weight if any, in order to overcome wind resistance, lifting mass up-hills at normal speed and also due to bearing and tire friction [3] and these forces acting are indicated in fig .2 as a mathematical model. This section focuses on bicycle performance, such as speed, grade ability, acceleration and also results obtained in MATLAB platform is shown.

A. Grading Resistance

when a bicycle goes up or down a slope , its weight produces a component of force that is always in the downward direction which either opposes forward motion during "grade climbing “or helps forward motion during "grade descending".

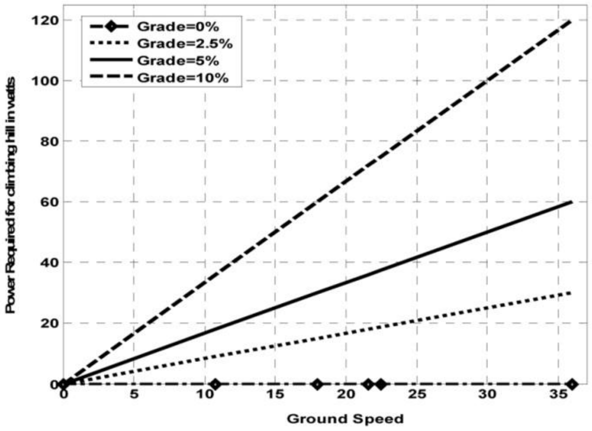

Fig.3 Power consumed in climbing hill

Hence, power is consumed to climb a grade and is a product of total mass and vertical speed

.P_h=9.81MV_gG Watts

Where M is total mass of bicycle, V_g is ground speed and G is the grade, expressed as elevation change over distance travelled. Fig 3 Illustrates plot of power consumed in climbing hill at different up-gradient for a given speed data.

B. Aerodynamic Drag

A bicycle travelling at a particular speed in air encounters a force resisting the motion. This force is referred to as aerodynamic drag and is given by

$F_w=C_d \wp A V_r^2/2$ Newton

Where A is frontal area which is exposed to wind, C_d is coefficient of drag, $\wp$ is density of air at a height above sea level and V_r is relative speed of vehicle to wind.

i.e, $V_r=V_w+V_g$

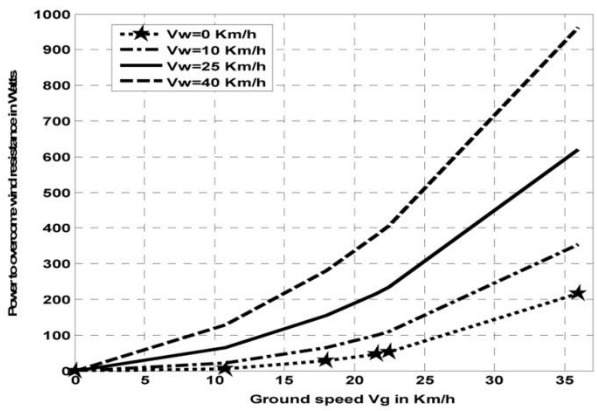

Fig.4 Power consumed to overcome wind drag

This force depends on the total shape of bicycle & rider and also depends on skin of bicycle body. This force creates a zone of low pressure which offers resistance to forward motion of bicycle. Hence, the power consumed in overcoming wind drag in each increment of travel is

$P_w=F_w V_g$ Watts

Fig.4 illustrates plot of power spent to overcome different wind drag for a given speed data.

C. Rolling resistance

The rolling resistance of tires on hard surface is primarily due to hysteresis in the materials. This causes an asymmetric distribution of the ground reaction forces. Hence power is required to overcome such forces and it also depends on the coefficient of rolling resistance whose value is different for a given surface. [4], the power consumed in overcoming such frictional forces is given by

$P_r=9.81 C_r M V_g$ Watts

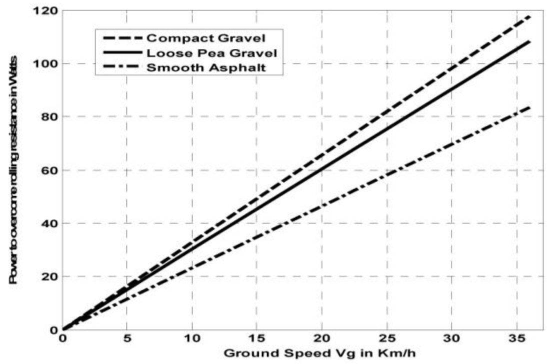

Fig .5 Power consumed at different surface friction

The plot of power invested at different surface friction is given in Fig.5. So, for road surfaces with high friction requires more power.

D. Power for Acceleration

The kinetic energy, K, invested into a moving object corresponds to one-half its mass times its velocity squared (K; = (1/2) Mv^2). A propelling force that exceeds the bicycle's windage and friction forces will raise the bicycle's kinetic energy content by raising its velocity. The force of acceleration is F = Ma. This force translates to torque required at the bicycle drive wheel that ultimately requires a torque from the motor and/or a force exerted by the rider on the crank pedals.

The torque required at the drive wheel for a given acceleration (a, mls ^{2}) is

T = 9.807Mr N-m

Where r is the wheel radius, expressed in meters, M is total bicycle and rider mass that is the combined weight in kilograms divided by the gravitational constant 9.807 mls^2•

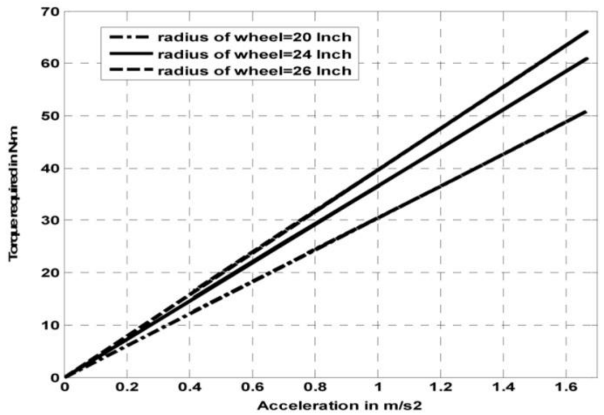

Fig.6 Torque obtained at for different wheel radius

From the plot shown in Fig.6 it is clear that, for given speed and power data if the radius of wheel is more the resulting torque is more and hence bicycle moves at less effort. Power consumed in bringing the bicycle in to motion is

P= (1/2)9.807Ma^2t Watts

Where a is acceleration in m/s^2 at a given time t in seconds. However, as starting torque depend on weight, moment of inertia of bicycle parts & rider and is near the stall torque of motor, at which current delivered from battery should be high. Hence, one of the solutions to avoid is by exerting force on the crank pedal by the rider which will subtract power as well as torque required from motor.

III. SELECTION OF BATTERY

The Power source for electric bicycle will be battery which is charged from 230V, 50Hz utility supply and even it can be charged from solar energy.

TABLE .1 PERFORMANCE COMPARISION OF THREE BATTERY TECHNOLOGIES

Parameters	Li-ion	Ni-MH	Lead-acid
Working voltage(V)	3.7	1.2	2.0
Gravimetric energy density(Wh/Kg)	130-200	60-90	30-40
Volumetric energy density (Wh/L)	340-400	200-250	130-180
Cycle life(cycles)	500	400	300
Capacity self-discharge rate (% per month)	5%	30%	10%
Energy efficiency)$C_{dicharge}/C_{charge}$)	99%	70%	75%
Weight comparison for same capacity	1	2	4
Size comparison for same capacity	1	1.8	3.5
Reliability	High	Low	High

While selecting batteries primary concern is cost, durability, energy density, and the number of recharge cycles. The most common batteries used are sealed lead acid batteries due to their low costs, but its relatively heavy weight and lesser life cycle this cannot be suitable for electric bicycle application [5]. Table.1 shows the performance comparison of three electro-chemistry namely Lead-Acid, Ni-MH and Li-ion.

As it is clear from Table.1 that, among these three battery technologies, Lithium-ion Battery is the best power solution for Electric Vehicle (EV) applications, because of its high energy density and long cycle life. Lead-acid Battery as an outdate technology has being used less and less for EV applications, due to its heavy weight, large size and non-environmental friendly for battery materials such as lead and sulfuric acid.

The other hand Li-ion battery technology has higher voltage rating and high reliability of 3.7V, which is three times greater than Ni-MH battery and hence requires less number of cells in series to increase voltage rating and hence increases its reliability compared to Ni-MH. It also gives 2 times longer distance ride than the Ni-MH battery can do.

A. Mathematical Model of L-ion battery

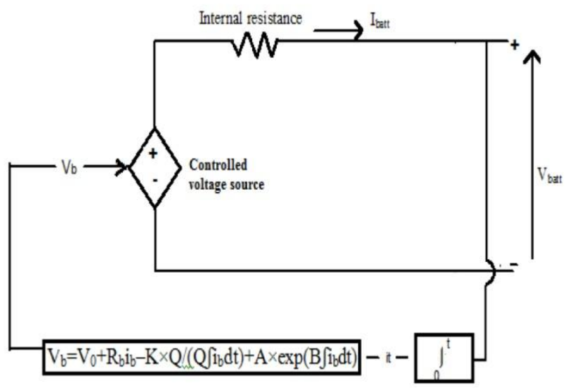

Fig. 7 Typical Li-ion battery models

Electric circuit-based models can be useful to represent electrical charectistics of batteries and most simple electric model of battery consists of an ideal voltage source in series with an internal resistance [6]. However, the electrochemical behaviour of a battery can be studied directly in terms of terminal voltage, open circuit voltage, internal resistance, discharge current and state-of charge. Fig.7 gives equivalent circuit of battery

IV. SELECTION OF MOTOR

The Hub motor is steadily emerging as the standard drive method for electric vehicles. Hub motors are electric motors which are built directly in to the hub of each wheel. Unlike conventional motors the hub motor has the inner portion held firmly and the outer portion which is rotating connected to spokes.

Performance requirement of motor for electric bicycle

- It should have short-term overload capability to meet requirement of accelerating or climbing.

- High degree of power density and better efficiency.
- Should reduce vehicle weight to extend driving range.
- Have good controllability, high steady precision, good dynamic performance.

TABLE .2 COMPARISONS OF BRUSHLESS DC MOTOR WITH BRUSHED DC MOTOR AND INDUCTION MOTOR.

Parameters	BLDC	Induction motor	Brushed DC motor
Speed-Torque C/H	Flat– enables operation at all speeds at rated load.	Non-linear low torque at low speed.	Moderately flat –At higher speeds, brush friction increases, reducing useful torque.
Output power and size	High-reduced size due to good thermal C/H and is light-weight.	Moderate-since both stator and rotor have windings output power to size is lower than BLDC	Moderate/low as there heat produced is dissipated in air gap hence increasing temperature.
Rotor inertia	Low-better dynamic C/H.	High- poor dynamic C/H	High-limiting dynamic c/h
Starting current	Draws only rated current-no special circuit is required.	Draws up to 6-7 times the rated current and therefore uses starter.	Draws rated current.
Control requirement	It is required to keep motor running and to vary speed.	No controller required for fixed speed and is required for variable speed.	Required only for variable speed

With the above shown comparison it is BLDC motor can be better suitable to construct light-weight electric bicycle with higher power density compared to Induction motor & DC motor.

V. BLDC BASED PROPULSION

A. Brushless DC motor Operation

A brushless DC (BLDC) motor is an inside-out permanent magnet DC motor, in which the conventional multi-segment commutator, which acts as a mechanical rectifier, is replaced with an electronic circuit to do the commutation. In a BLDC motor permanent magnets are mounted on the rotor with the armature windings being housed on the stator with a laminated steel core, as illustrated in Figure.8 BLDC motor consist of stator coils, rotor permanent magnets, electronic commutator and hall sensor to sense position of rotor and help in commutation process in order have continues rotation of motor.

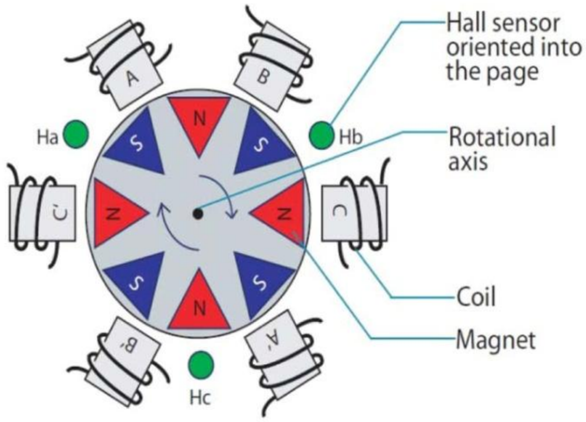

Fig 8 Permanent magnet BLDC construction

B. Inverter for BLDC motor

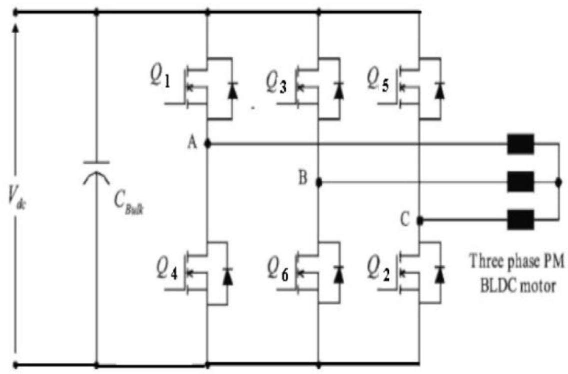

Fig 9 Three Phase Hex-bridge Inverter

Rotation in BLDC is initiated and maintained by sequentially energizing opposite pairs of pole windings/phases i.e voltage stokes are applied to the two phases of 3-phase winding system so that the angle between the stator flux and the rotor flux is kept close to 90 degrees in order to generate maximum torque from the motor. This is done by an electronic switching using H-bridge inverter as shown is Figure 9. This stage consist of six semi-conductor switches usually power MOSFET is preferred due to its high switching frequency >MHz, voltage rating up to 600V with lower switching and conduction losses.

It is critical to know the rotor position for energizing appropriate windings of stator to sustain motion. The rotor position information can be obtained from Hall Effect sensors. Usually three hall sensors are used and placed 120 degree mechanically apart such that each sensor outputs a high level for 180 degree of an electrical rotation, and a low level for the other 180 degree [7]. The three sensors have 60 degree relative offset from each other and this divides the rotation in to six-phase. Table. 3 show the relationship between the hall sensor input code, the required active motor windings.

TABLE.3 SENSOR INPUT BY ACTIVE SWITCH TABLE

Theta_elec	Hall sensor	Commutation no:	Active drive	
0°-60°	101	1	Q1(PWM1)	Q6(PWM6)
60°-120°	100	2	Q1(PWM1)	Q5(PWM5)
120°-180°	110	3	Q3(PWM3)	Q5(PWM5)
180°-240°	010	4	Q3(PWM3)	Q4(PWM4)
240°-300°	011	5	Q2(PWM2)	Q4(PWM4)
300°-360°	001	6	Q2(PWM2)	Q6(PWM6)

C. Modeling of BLDC motor

BLDC motor can be realized mathematically in two ways: abc-phase variable model and d-q axis model. In a BLDC motor, the trapezoidal back EMF implies that the mutual inductance between stator and rotor is non-sinusoidal, thus transforming to d-q axis does not provide any particular advantage, and so abc phase variable model is preferred. In this electrical & mechanical system of BLDC motor is discussed [8]. Following series of equations expressed for electrical system is for abc-phase variable model & it is noted that phase inductance Ls is assumed constant and does not vary with rotor position.

$$\frac{d}{dt}i_a = \frac{1}{3L_s}(2v_{ab} + v_{bc} - 3R_s i_a + \lambda p\omega_r(-2\varphi'_a + \varphi'_b + \varphi'_c)) \quad (1)$$

$$\frac{d}{dt}i_b = \frac{1}{3L_s}(-v_{ab} + v_{bc} + 3R_s i_b + \lambda p\omega_r(\varphi'_a - 2\varphi'_b + \varphi'_c)) \quad (2)$$

$$\frac{d}{dt}i_c = -(\frac{d}{dt}i_a + \frac{d}{dt}i_b) \quad (3)$$

$$T_e = p\lambda(\varphi'_a.i_a + \varphi'_b.i_b + \varphi'_c.i_c) \quad (4)$$

Where

Ls = Inductance of the stator windings

R = Resistance of the stator windings

i_a, i_b, i_c =a, b and c phase currents

$\varphi'_a, \varphi'_b, \varphi'_c$=a, b and c phase electromotive forces

v_{ab}, v_{bc}=ab and bc phase to phase voltages

ω_r=Angular velocity of the rotor

λ = Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases

P = Number of pole pairs

T_e = Electromagnetic torque

The mechanical system is expressed using following equations (4) & (5)

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - T_f - F\omega_r - T_m) \quad (5)$$

$$\frac{d\theta}{dt} = \omega_r \quad (6)$$

Where

J =Combined inertia of rotor and load

F = Combined viscous friction of rotor and load

θ = Rotor angular position

T_m= Shaft mechanical torque

T_f = Shaft static friction torque

Table.3 shows the modeling of motor including realization of hall sensors as a function of rotor electrical angle.

VI. SIMULATION RESUTS

The charging & discharging characteristics waveform of Li-ion battery with resistive load of 100 ohm is illustrated with voltage, SOC and current waveforms of battery in Fig.10. The battery voltage, current and state-of-charge when connected to BLDC motor is sown in Fig .11 and it is noted that the current drawn from battery shoots to 1200A as soon as motor is powered for an instant to meet the torque requirement and after 0.2s, its value settles between 1.2-2.8A the value of SOC slowly drops from 100% to 99.984% in 2s.

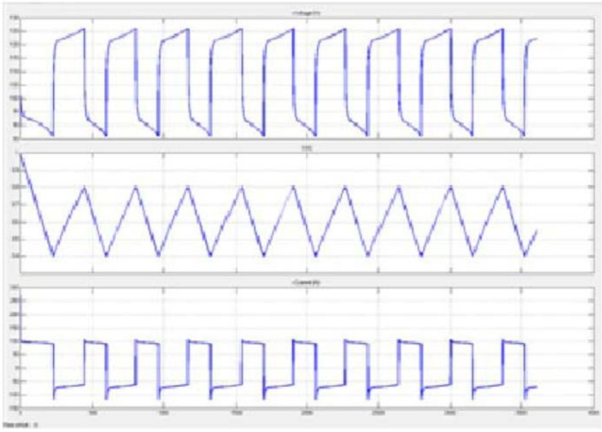

Fig .10 Waveforms of voltage, SOC and current from Li-ion battery

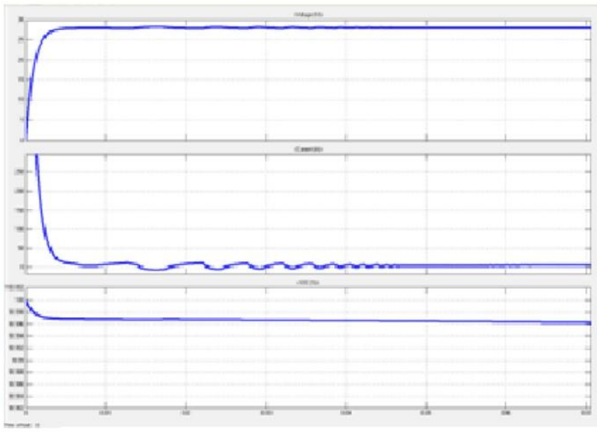

Fig .11 Waveforms of voltage, SOC and current from Li-ion battery connected to BLDC motor

Stator phase currents i_a, i_b and i_c shown in Fig.12 are 120 degrees apart from each other with motor torque applied externally is of 3 N-m. Rotor speed is at 170 rpm and attains after 0.2s which is shown below phase currents. Though there is ripple in electromagnetic torque Te but, this is not reflected at rotor speed and helps in smooth operation of motor.

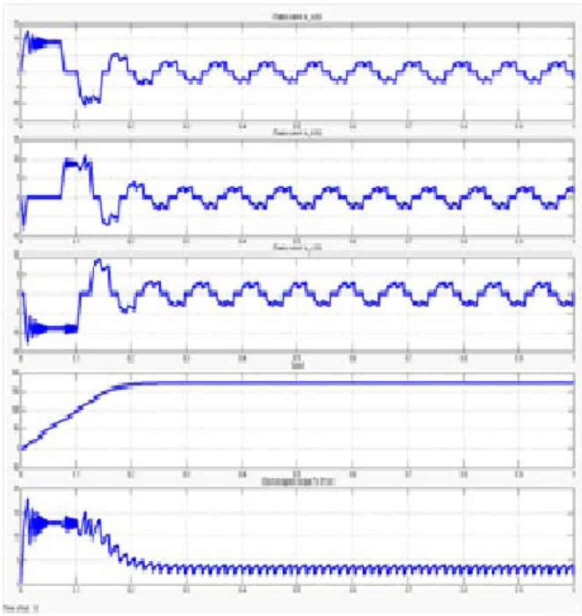

Fig .12 Waveforms of three stator phase currents, rotor speed and electromagnetic torque of BLDC motor

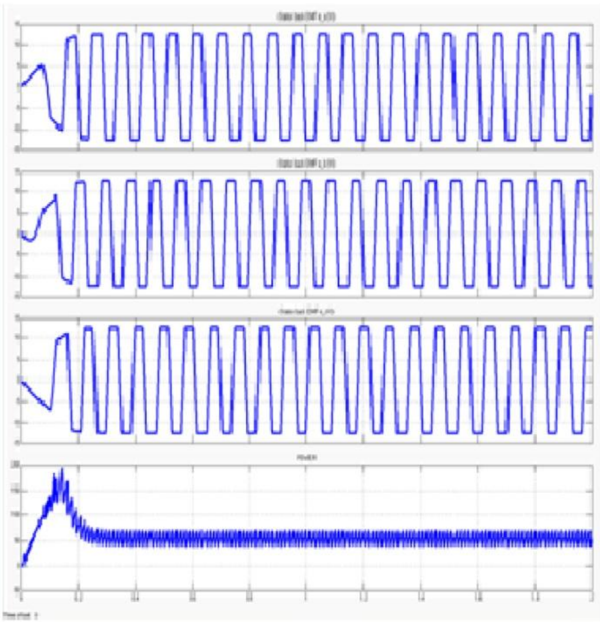

Fig .13 Waveforms of three back-emf induced, power output of BLDC motor

Simulation results shown in Fig.13 gives the three back emf induced in each phase which is displaced at 120 degrees from each other with peak-peak value of 25volts. The output power curve from the motor shown below back-emf has shoot between 0-0.2s interval due to which high current was drawn from the battery as discussed in battery simulation waveforms and then draws power varying from 40W to 70W due to torque ripples.

CONCLUSION & FUTURE WORKS

The results illustrated in this paper can help in systematic study of electric propulsion and design an electric bicycle to the ratings of one's requirement & can be extendable to tricycle application for physically challenged society. Here electric propulsion system using BLDC motor with sensory speed control along with smooth running operation is shown & in future sensor less operation with added complexity can be adopted to overcome limitations & expenses of sensors. The system performance can be improved if renewable energy sources like solar power can be employed. Also efficient modern day energy storage devices like Ultra capacitors and even fuel cell technology can be integrated as a source of power.

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