System Design of Electric Bicycle Performance and Solar PV Parking

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***Abstract*-- Electric bicycle usage is considered as an option for low carbon green transport. It is suitable for short range mobility both in the city and rural areas. When integrated with renewable energy source, sustainable and green mobility can be realized. To synchronize the renewable power source and the energy demand by the electric bicycle, system design can be introduced to simulate and determine the power supply based on energy requirement on the performance of electric bicycle. Then, the simulated results are analyzed as criteria for sizing of the mobile solar PV charging station prototype. The results indicate that system design can be employed as feasibility study and design exploration for such mobility.**

***Index Terms*-- Electric bike performance, PV parking, system design, and sustainable mobility, green transport.**

I. Introduction

Electric bicycle usage is considered as an option for low carbon green transport [2],[3],[7]. It is suitable for short range mobility both in the highly populated city and rural areas. When integrated with renewable solar PV electrical source, sustainable and green mobility can be realized [1],[4]. This can be done by synchronizing the renewable power source and the energy demand by the electric bicycle where the physical diagram can be presented in Fig. 1. The electric bicycle can be parked and charged from mobile PV charging station [1]. However, sizing of PV panel rooftop is needed for constructing the station with low cost and saving time for trials. As a result, system design can be introduced to simulate and determine the power supply based on energy requirement obtained from driving load of electric bicycle.

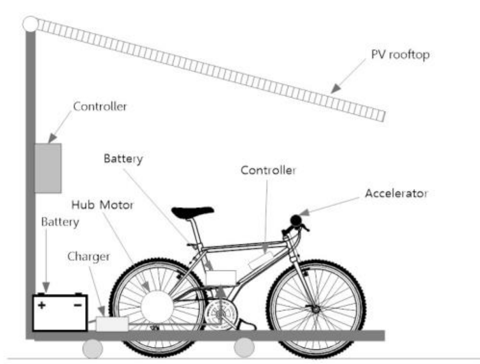

Fig. 1. Integration of solar PV mobile station with electric bicycle.

II. Methodology

System design for solar PV sizing can be divided into 5 procedures as seen in Fig. 2, which are first, electric bike requirement and specification is obtained, and then each main electric bicycle is modeled, and components are integrated for modeling power flow with in electric bicycle [1]. Then, performance and driving range of the electric bicycle is simulated for solar PV load sizing analysis and design. Illustration in details is presented later on in this section.

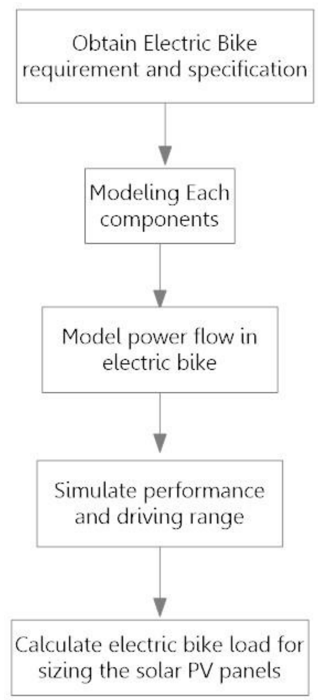

Fig. 2. System design procedures for solar PV sizing based on electric bicycle driving load simulation.

A. Specify Electric Bicycle Requirement and Specification

Electric bicycle specifications are approximately used as the input for the simulation study. Other input parameters are the motor specification and road condition as listed below in TABLE I;

TABLE I
ELECTRIC BICYCLE COMPONENT SPECIFICATIONS AND REQUIREMENTS

Components	Descriptions
1. Bicycle body:	
Mass	23 kg
Passengers mass	70 kg
Coeff. of drag	0.9
Frontal area	0.6 m^2 (H x W)
Tire radius	19" (0.48 m)
Moment of inertia	Add 5% to bicycle weight kg
Rolling resistance	0.005
2. Transmission:	
Gear ratio	1
Gear efficiency	100% (app)
3. Motor:	
Motor efficiency	90% (app)
Regenerative ratio	0%
Power	250 w (cont.)
4. Battery:	
Type	Li-on
Peukert coeff.	1
No of cell	6
Cell voltage	12
Capacity (Ah)	30
Accessories loss	0 w
limit discharge	100%
- Open circuit voltage constant	
5. Driving condition:	
Day or night	All day
Road condition	Long smooth surface
Driving cycle	Bicycle Riding Cycle, constant
	Speed 20 km/hr
6. Performance:	
Maximum Bicycle speed	40 km/h

B. Model Electric Bicycle Components

In order to set up the simulation of electric bicycle as presented in Fig. 3, mathematical models have to be generated first from the engineering principles and theories [5]. The core models for components are traction model, motor model, and battery model [6].

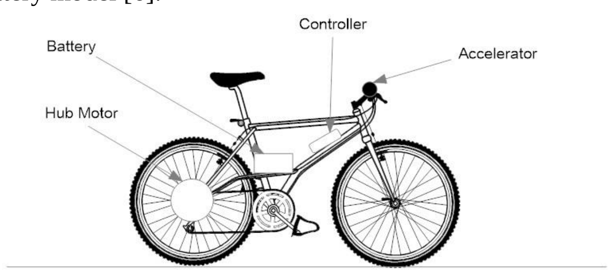

Fig. 3. Electric Bicycle components consist of hub motor, battery pack, controller and accelerator.

1) Traction Model

Forces acting on the vehicle govern the equation for vehicle traction as seen in Fig. 4. Those forces comprised of tractive forces (F_{te}), rolling resistance force (F_{rr}), aerodynamic force (F_{ad}), lateral acceleration force (F_{al}), wheel acceleration force $(F_{\omega a})$, hill climbing force (F_{hc}) [or component force of vehicle weight], and the weight of the vehicle itself.

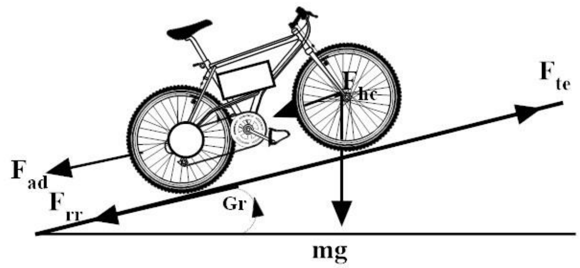

Fig. 4. The force components involved in the electric bicycle traction.

The relation is shown in (1) where traction needs to overcome the load is equal to five other forces;

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{wa} \quad (1)$$

Where equation for each force components can be written as following;

$$F_{hc} = mg\sin(\theta) \quad (2)$$

$$F_{rr} = \mu_{rr} mg \quad (3)$$

$$F_{ad} = \frac{1}{2}\rho A C_d v^2 \quad (4)$$

$$F_{\omega a} = I\frac{G^2}{\eta_g r^2}a \quad (5)$$

$$F_{la} = ma \quad (6)$$

The rolling resistance force (2) depends on both the weight of vehicle and rolling resistance (μ_{rr}) in. Also, frontal area(A), drag coefficient(C_d), vehicle speed(v), and the air density (ρ) all contribute for the aerodynamic load in(4). The wheel load when vehicle accelerate $(F_{\omega a})$ can be calculated using moment of inertia(I), gearing ratio(G), gearing efficiency (η_g), the tire radius, and vehicle acceleration as presented in(5). When the vehicle accelerates also produce the load due to the law of motion in (6).

For the electric bicycle, traction model is divided into two phases due to the motor traction characteristics. Motor is operated at maximum torque $(T_{\max})$ and then torque is declined with constant motor power $(T_{P_{const}})$ as a motor characteristic is field weakening. The point where motor characteristics start to change is called critical speed(ω_c). Then the traction model becomes as follows;

- Phase 1: $T = T_{\max}$

$$\eta_g \frac{G}{r} T_{\max} = \mu_{rr} mg + \frac{1}{2}\rho A C_d v^2 + \left(m + I\frac{G^2}{\eta_g r^2}\right)\frac{dv}{dt} \quad (7)$$

- Phase 2: $T = T_{P_{const}} = \dfrac{rT_{\max}\omega_c}{Gv}$

$$\eta_g \frac{G}{r} T_{P_{const}} = \mu_{rr} mg + \frac{1}{2}\rho A C_d v^2 + \left(m + I \frac{G^2}{\eta_g r^2} \right) \frac{dv}{dt} \quad (8)$$

2) Motor Model

In the electric bicycle system, the motor replace pedaling to drive the wheel by providing torque, which also affects the traction of the bicycle. The motor torque, speed and efficiency equation are presented in (9) (10) and (11) respectively.

- Motor torque (T)

$$T = \frac{F_{te} r}{G} \text{ (N.m)} \quad (9)$$

- Motor angular speed (ω)

$$\omega = G\frac{v}{r} \text{ (rad.s}^{-1}\text{)} \quad (10)$$

- Motor efficiency (η_m)

$$\eta_m = \frac{T\omega}{T\omega + k_c T^2 k_i \omega + k_\omega \omega^3 + C} \quad (11)$$

Where k_c is copper losses coefficient, k_i is iron losses coefficient, k_ω is windage loss coefficient, and C is constant loss applied at any speed.

3) Battery Model

Battery's dynamic behavior does have and greatly effect on bicycle range. Three common type of Lithium Ion battery will be modeled here. Open circuit voltage (E) of the batteries is changed as the state of charge changes, and is calculated for Lithium ion battery type below;

$$E = n \cdot 3.3 \quad (12)$$

(Nominal cell voltage = 3.3 V up to 80% *DoD*) Where n is number of cells, and DoD is Depth of discharge (0 to 1) The open circuit voltage also affects the batter current (I_B) in both state of charge and discharge.

- Battery current discharge operating at power (P_{bat})

$$I_B = \frac{E - \sqrt{E^2 - 4RP_{bat}}}{2R} \quad (13)$$

- Battery current charge during regenerative braking

$$I_B = \frac{-E + \sqrt{E^2 + 4RP_{bat}}}{2R} \quad (14)$$

Where R is the battery resistance.

Batteries tends to draw charge more than usual when discharge at higher current due to Peukert phenomenon, therefore it is necessary to take in account of such effect by adding the power to the k value and Lithium ion has $k \approx 1$, when simulation of battery discharge is performed.

Battery capacity (CR) is updated for each time step (δt) as shown in (15), and then used to update depth of discharge (DoD) in (16) for discharging state and in (17)

- Total charge removed from battery by the n^{th} step of the simulation

$$CR_{n+1} = CR_n + \frac{\delta t \cdot I_B{}^k}{3600} \quad (15)$$

- The depth of discharged

$$DoD_n = \frac{CR_n}{C_p} \quad (16)$$

- Charge removed for regenerative braking

$$CR_{n+1} = CR_n - \frac{\delta t \cdot I_B}{3600} \quad (17)$$

C. Incorporate All System Components to Determine Power Flow Model

To complete the simulation, the integrated power flow model is necessary to compute and update the rate of energy going in and out of battery cells, accessories, the motor, transmission, and wheel to the road and back. Therefore, the model needs to be capable of mathematically simulating the power flow in both driving and braking as shown in Fig. 5.

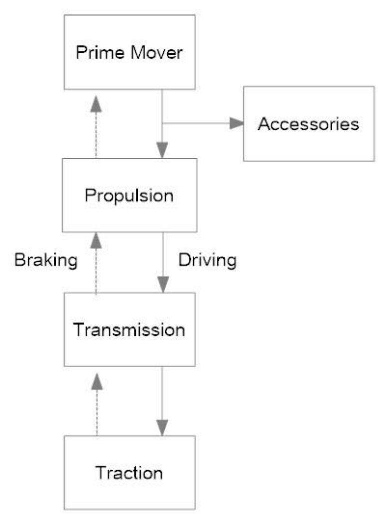

Fig 5. Diagram show power flow in/out components within the electric bicycle system for both normal forward driving and regenerative braking operations [6].

Traction model provides the power flow between the vehicle and the road (P_{te}) as shown in (18). Furthermore, the motor model provides the power going in for both driving and braking mode at the motor to batteries connection (P_{mot_in}) and at the motor/transmission connection (P_{mot_out}) as indicated in (19) and (20). The power parameters are affected by the motor efficiency (η_m) and the gearing efficiency (η_g). The battery power is also computed and updated in (21) during charge and discharge operation using the battery model. Power (P_{ac}) is constantly drawn out of battery due to use of accessories, such as light, which is accounted in (21).

- Energy required each second

$$P_{te} = F_{te} \cdot v \tag{18}$$

- Motor power in driving mode

$$P_{mot\_in} = \frac{P_{mot\_out}}{\eta_m}, \quad P_{mot\_out} = \frac{P_{te}}{\eta_g} \tag{19}$$

- Motor power in braking mode

$$P_{mot\_in} = P_{mot\_out} \cdot \eta_m, \quad P_{mot\_out} = P_{te} \cdot \eta_g \tag{20}$$

- Battery power

$$P_{bat} = P_{mot\_in} + P_{ac} \tag{21}$$

D. Simulate Performance and Driving Range for Designing Load Analysis

For electric bike performance simulation, the traction model equation (7) and (8) is reduced to nonlinear first order differential forms in (24) and (25) when all inputs are substituted;

- Phase 1: $T = T_{\max}$
  Substitute;

$$\frac{dv}{dt} = 1.54 - 0.000244v^2 \tag{22}$$

- Phase 2: $T = T_{P_{const}} = \frac{40000}{\omega}$

$$\frac{dv}{dt} = \frac{18.26}{v} - 0.118 - 0.000244v^2 \tag{23}$$

Then, differential equation of velocity (22) and (23) are numerically solved using the MATLAB script (.m) file for each time step and update the values in the program arrays [1],[5]. The out velocity can be plotted against time. The electric bicycle performance here is specified as the time for electric bicycle to accelerate form 0 to 40 km/h.

In order to perform the analysis, the motor model, battery model and power flow model introduced in the previous section are applied here along with additional inputs. Driving cycle need to be reasonably selected to simulate the driving dynamics. For simplifying simulation, constant 20 km/hr is applied since the bicycle is expected to be riding at constant speed most of time. The detail of programing can be studied in [5].

E. Calculate Amount of Electricity Required for Solar PV from Electric Bicycle Driving

The simulated driving range (R_D) (km) and motor output (P_m) (w) values can be employed to obtain electricity load (E_l) (whr) required from solar PV in (24). The driving range per charge (R_D) and driving velocity (v) (km/hr) can used to calculate lapse time (T_D) for electric bicycle riding in (25). Then, the energy required from solar PV charging station can be determined from motor power output and lapse time (hr).

$$E_l = \int_0^t P_m dt = P_m t \quad \text{(whr)} \tag{24}$$

Where

$$t = \frac{R_D}{v} \quad \text{(hr)} \tag{25}$$

III. Results and Discussion

For electric bicycle performance, current specification indicate that requirement for top speed of 40 km/hr can be met as seen in Fig. 6 below. The electric bicycle can accelerate from 0 to 20 km/hr in 15 seconds.

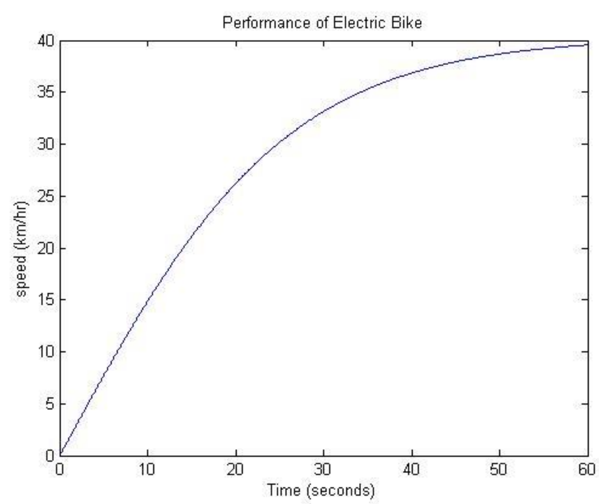

Fig. 6. Simulated performance of the electric bicycle.

For electric bicycle driving load as shown in Fig. 7, the results has shown the electric bicycle can travel as far as 14 km before the battery run out in full electric mode (without pedaling). The results are simulated based on the input specification and some approximated parameters presented in TABLE I.

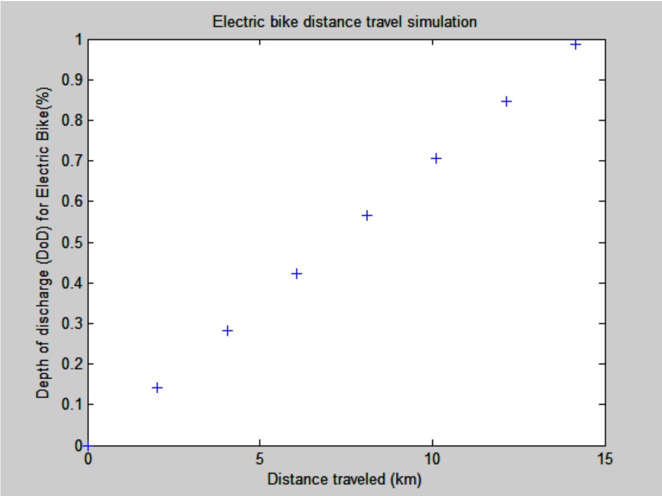

Fig. 7. Electric bicycle distance traveled simulation based on *DoD* of the battery.

The motor power output can also be simulated to indicate power required for driving electric bicycle. From Fig. 8, the motor power usage is constant at 83 W throughout the driving cycle since the driving cycle for electric bicycle is selected to be constant at 20 km/hr.

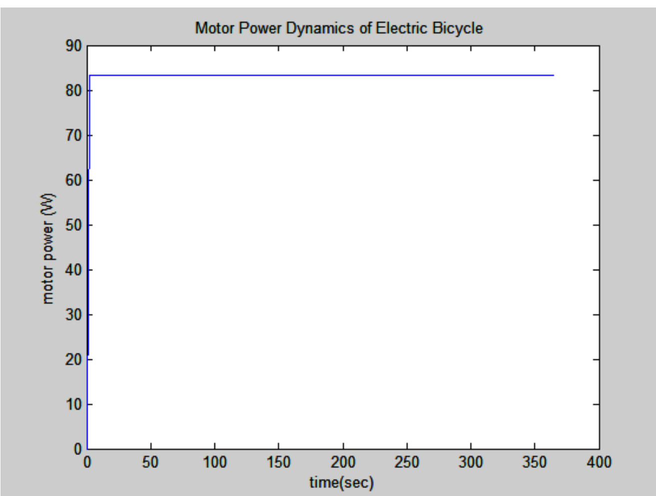

Fig. 8. Motor power output of the electric bicycle in full electric mode.

From the specification, bicycle is expected to be rode at constant speed of 20 km/hr for with total distant of 14 km before battery run out $(DoD \approx 100\%)$. By applying equation (26), the total driving time is determined to be 42 minutes. As a results, total electricity usage is estimated to be only 58 whr, employing (24), which can be easily charged through the mobile charging station.

The results demonstrate small amount of electricity required to charge electric bicycle per day. This means that mobile solar PV station can be feasible since it is only need electricity about 0.06 unit (1 unit = 1 kwhr) per day for charging one electric bicycle. Fig. 9 shows prototype of mobile charging station where the system configuration in TABLE II is determined according to simulation analysis.

TABLE II
MOBILE SOLAR PV CHARGING STATION FOR ELECTRIC BICYCLE

Component	**Specification**
PV module	100 w, Size: 110x71.5x8 cm
Battery	12V 100 Ah
Controller	12-24 V
Inverter	300-400W, 12 VDC to 220 VAC

The electric bike can be parked and charged throughout the day or at night and the assembled station can be placed at any outdoor location as seen in Fig. 10. Nevertheless, the actual charging data are needed to be collected in the future to validate the sizing of solar mobile charging station and tuning for improvement of the system. The range per charged for riding electric bicycle can also be examined to calibrate with the mobile charging station. Moreover, system design can be applied for the design of multiple electric bikes charging station if needed.

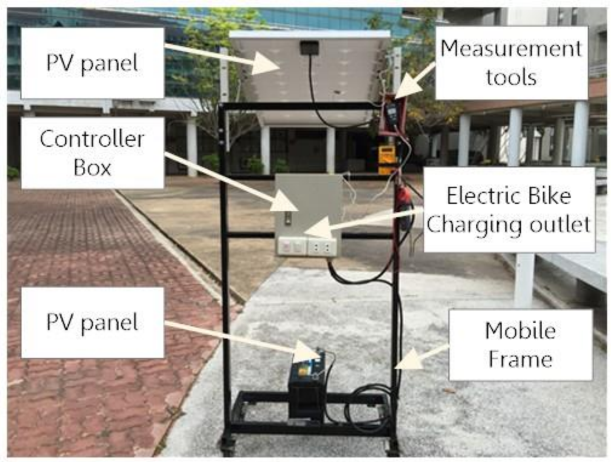

Fig. 9. The prototype of solar PV mobile charging station for electric bike.

Fig. 10. Demonstration of electric bike parking and charging to solar PV mobile charging station.

IV. Conclusion

This study demonstrates the benefit of system design in enabling feasibility analysis and design exploration of solar PV mobile charging station. The methodology can be employed based on simulation of electric bicycle specification and requirements to reduce design trial time and fabrication cost. Employing such methodology can also facilitate the right design and prototype of green and sustainable mobility.

V. Reference

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