Designing optimal speed control with observer using integrated battery-electric vehicle (IBEV) model for energy efficiency

By Rina Ristiana

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Rina Ristiana [a, b, *], Arief Syaichu Rohman [a], Estiko Rijanto [c], Agus Purwadi [a], Egi Hidayat [a], Carmadi Machbub [a]

[a] School of Electrical Engineering and Informatics, Institut Teknologi Bandung
Jl. Ganesha No. 10, Bandung, West Java, Indonesia
[b] Instrumentation Development Unit, Indonesian Institute of Sciences
Komplek LIPI Jl. Sangkuriang, Bandung, West Java, Indonesia
[c] Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences
Komplek LIPI Jl. Sangkuriang, Bandung, West Java, Indonesia

Abstract

This paper develops an optimal speed control using a linear quadratic integral (LQI) control standard with/without an observer in the system based on an integrated battery-electric vehicle (IBEV) model. The IBEV model includes the dynamics of the electric motor, longitudinal vehicle, inverter, and battery. The IBEV model has one state variable of indirectly measured and unobservable, but the system is detectable. The objectives of this study were: (a) to create a speed control that gets the exact solution for a system with one indirect measurement and unobservable state variable; and (b) to create a speed control that has the potential to make a more efficient energy system. A full state feedback LQI controller without an observer is used as a benchmark. Two output feedback LQI controllers are designed; including one controller uses an order-4 observer and the other uses an order-5 observer. The order-4 observer does not include the battery state of charge as an observer state whereas the order-5 observer is designed by making all the state variable as the observer state and using the battery state of charge as an additional system output. An electric passenger minibus for public transport with 1500 kg weight was used as the vehicle model. Simulations were performed when the vehicle moves in a flat surface with the increased speed from stationary to 60 km/h and moves according to standard NEDC driving profile. The simulation results showed that both the output feedback LQI controllers provided similar speed performance as compared to the full state feedback LQI controller. However, the output feedback LQI controller with the order-5 observer consumed less energy than with the order-4 observer, which is about 10% for NEDC driving profile and 12% for a flat surface. It can be concluded that the LQI controller with order-5 observer gives better energy efficiency than the LQI controller with order-4 observer.

Keywords: integrated battery-electric vehicle (IBEV) model; speed control; electric vehicle; linear quadratic integral; observer system; energy efficient.

I. Introduction

In the future, electric vehicles will be more widely used for mass transportation, implemented in special lines empowered by automatic systems such as driverless systems, assisted drive systems, self-driving systems and so on. This prospect has opened up new research areas for innovation in technology based on automation of specifically controlled systems. One of the limitations of electric vehicles is the limited amount of energy they can carry, which is mainly stored in its battery [1]. Assuming that this limited capacity is because of existing battery technology, the problem should be solved using an energy-efficient strategy [2].

Energy-efficient strategies for electric vehicles are one of several types of strategies that involve control design of the vehicle. The control design of an electric vehicle is implemented with vehicle/motor speed control [3] and torque control [4][5].

An important factor in designing such a control system is the electric vehicle model. In [3] and [4] an electric vehicle model with battery dynamics integrated into the system was presented. The use of an integrated

* Corresponding Author. Tel: +62 813 7991 7553
E-mail address: rina005@lipi.go.id

model in electric vehicle control design (speed or torque) has been shown to have potential in achieving a more energy-efficient system. Although the integrated model has one unobservable state variable, the system is still detectable.

Ideally, all state variables should be available for feedback in the system, but not all state variables are available for feedback. Therefore, it needs to estimate unavailable state variables. Estimation of unavailable state variables is called state observer. A state observer estimates the state variables based on the measurements of the output and control variables. The observers consist of: a full-order observer that is used to estimate all the state variables of the system that are considered available for direct measurement [6].

This paper describes how to design an optimal speed control using the LQI control standard with/without an observer in the system. The goals of this research were to create a control design: (a) that gets the exact solution for one state variable in the system which is unobservable and can only be measured indirectly, and (b) has the potential to be more energy efficient. The LQI control systems have been built in three cases, i.e. LQI control without observer (assumption that all variables are available for feedback), LQI control with an order-4 observer (ignoring one state variable of the system during designing the observer), and LQI control with an order-5 observer (adding one state variable in the output of the system), which were compared to find the best response characteristics and to increase energy efficiency.

II. Materials and methods

A. Integrated battery-electric vehicle (IBEV) model

The battery-electric vehicle (BEV) model was built as an integrated model. This means that it is a model with battery dynamics involved in the system (Figure 1). It includes an electric motor [7], an inverter [8], a longitudinal vehicle [9], and battery dynamics [10][11].

The integrated model is a linearized model derived from a nonlinear model. It is assumed that only the battery supplies the electric motor of the vehicle, hence the current of the battery are the same as the motor current. The gear trains have no backlash; they are rigid bodies. The shaft stiffness and each gear ratio are proportional to the radius of the gear [9]. The longitudinal dynamic equations were influenced by traction, acceleration, and total resistance forces as load (see Figure 1). The total resistance forces included drag force, gradient force, rolling resistance force, and curvature resistance force [12].

According to [4], differential equations of the motor speed (1), the motor current (2), the first (3) and the second (4) capacitor voltage of the battery, and the charge extracted from the battery (5) respectively can be written as:

$$\frac{d\omega_m(t)}{dt} = -\frac{b_m}{nJ_{tot}}\omega_m(t) + \frac{k_t}{nJ_{tot}}i_m(t) - \frac{n^2K_dr_w{}^3}{2J_{tot}}\omega_m{}^2(t) + \frac{m_v r_w g}{J_{tot}}\left(\sin\theta + C_{Rx}\cos\theta + \frac{k_{tk}}{R}\right) \quad (1)$$

$$\frac{di_m(t)}{dt} = -\frac{k_e}{L_m}\omega_m(t) - \frac{R_m}{L_m}i_m(t) + \frac{K_c}{L_m}(-R_d i_m(t) - V_{c1}(t) - V_{c2}(t) + 2a_1 SOC_n(t) + 2a_1 + 2a_0)u_c(t) \quad (2)$$

$$\frac{dV_{c1}(t)}{dt} = -\frac{1}{R_{t1}C_{t1}}V_{c1}(t) + \frac{1}{C_{t1}}i_b(t) \quad (3)$$

$$\frac{dV_{c2}(t)}{dt} = -\frac{1}{R_{t2}C_{t2}}V_{c2}(t) + \frac{1}{i_b(t)/C_{t2}}i_b(t) \quad (4)$$

$$\frac{dSOC_n(t)}{dt} = -\frac{1}{Q_n}i_b(t) \quad (5)$$

The battery voltage can be represented as:

$$V_b(t) = V_{OC}(t) - R_d i_b(t) - V_{c1}(t) - V_{c2}(t) \quad (6)$$

The open-circuit voltage (two batteries) is $V_{OC}(t) = 2a_1SOC(t) + 2a_0$ and the state of charge is $SOC(t) = (SOC_0(t) + SOC_n(t))$ with $SOC_0(t) = Q_0/Q_n = 1$, where R_d, i_b, R_{t1}, C_{t1}, R_{t2}, C_{t2}, a_1, a_0, Q_0 and Q_n are suitable constants [4][11].

The state variables are defined as $x_1(t) = \omega_m(t)$, $x_2(t) = i_m(t)$, $x_3(t) = V_{c1}(t)$, $x_4(t) = V_{c2}(t)$ and $x_5(t) = SOC_n(t)$ and the output variable as $y(t) = \omega_m(t) = x_1(t)$.

From equation (1) to (5), the state equation may be described as:

$$\dot{x}_v(t) = f(x_v(t)) + g(x_v(t))u_c(t) + Hd_L$$
$$y_v(t) = C_v x_v(t) \quad (7)$$

Its matrices are given by:

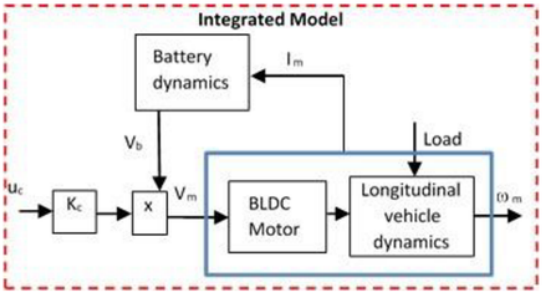


Figure 1. Integrated battery-electric vehicle (IBEV) model [4]

$$f(x_v(t)) = \begin{bmatrix} a_{11}+a_{NL} & a_{12} & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & 0 & 0 \\ 0 & a_{42} & 0 & a_{44} & 0 \\ 0 & a_{52} & 0 & 0 & 0 \end{bmatrix},$$

$$g(x_v(t)) = [0 \quad g_2 \quad 0 \quad 0 \quad 0]^T,$$

$$H = [1 \quad 0 \quad 0 \quad 0 \quad 0]^T,$$

$$C_v = [1 \quad 0 \quad 0 \quad 0 \quad 0],$$

where:

$a_{11} = -b_m/nJ_{tot}$, $a_{NL} = n^2K_d r_w{}^3 x_1{}^2(t)/2$,

$a_{12} = k_t/nJ_{tot}$, $a_{21} = -k_e/L_m$,

$a_{22} = -R_m/L_m$, $a_{32} = 1/C_{t1}$,

$a_{33} = 1/R_{t1}C_{t1}$, $a_{42} = 1/C_{t2}$, $a_{44} = 1/R_{t2}C_{t2}$,

$a_{52} = 1/Q_n$, $J_{tot} = (m_v r_w n + J_{eq}) r_w$,

$J_{eq} = J_m + (J_t/n_g{}^2) + (J_w/n_g{}^2 n_t{}^2)$, and

$g_2 = -(R_d x_2(t) + x_3(t) + x_4(t) - 2a_1 x_5(t) - 2(a_0 + a_1))K_c/L_m$.

With $K_d = \rho C_d A_f$; m_v, r_w, ρ, C_d, A_f, C_{Rx}, g, θ, k_{tk}, R, R_d, i_b, R_{t1}, C_{t1}, R_{t2}, C_{t2}, a_1, a_0, Q_0, Q_n, L_m, R_m, k_e, , $n=1/n_g\eta_g n_t\eta_t$; η_g and η_t are suitable constants [4].

B. Control system design

The speed control system was designed using the linear control integral (LQI) method. The LQI computes an optimal state feedback control law for the tracking loop with the assumption that all state variables are available for feedback in the system. In this paper, three LQI controllers are designed, i.e. a state feedback LQI controller and two output feedback LQI controllers with observer systems such as order-4 observer and order-5 observer. The state feedback LQI controller is used as a benchmark for comparison study. Luenberger observer is used in each output feedback LQI controller [13].

The first purpose of the LQI controller design is that the control design can answer in a proper way if there is a state variable in a system that is indirectly measurable and unobservable. The second purpose is to get one control design that has the potential to be more energy efficient.

1) LQI control

The LQI control used is as shown in Figure 2. Based on (7), by ignoring d_L, a linearized plant can be derived as follows:

$$\dot{x}_v(t) = A_v x_v(t) + B_v u_c(t)$$

$$y_v(t) = C_v x_v(t) \tag{8}$$

The set point tracking is given by:

$$\dot{x}_i(t) = r(t) - C_v x_v(t) \tag{9}$$

The full state feedback control is:

$$u_c(t) = -k_v x_v(t) - k_i x_i(t) = -K_z x_z(t) \tag{10}$$

The augmented state equation is obtained from [13] is:

$$\dot{x}_z(t) = A_z x_z(t) + B_z u_c(t) + G_z r(t) \tag{11}$$

where

$$A_z = \begin{bmatrix} A_v & 0 \\ -C_v & 0 \end{bmatrix},$$

$$B_z = \begin{bmatrix} B_v \\ 0 \end{bmatrix},$$

$$G_z = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \text{ and}$$

$$x_z(t) = [x_v(t) \quad x_i(t)]^T.$$

To stabilize the system of (11), a state feedback controller can be designed using $K_z = -R^{-1}B_z{}^T P$, by assuming $R > 0$ and $Q \geq 0$, P is the solution of the following algebraic Ricatti equation:

$$Q + A_z{}^T P + P A_z - P B_z R^{-1} B_z{}^T P = 0 \tag{12}$$

Such a feedback controller minimizes the following performance index:

$$J = \int_0^\infty (x_z(t)^T Q x_z(t) + u_c(t)^T R u_c(t))\, dt \tag{13}$$

The closed-loop system using LQI control with reference input is described by the augmented state equation that is obtained from:

$$\begin{bmatrix} \dot{x}_v \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A_v - B_v K_z & 0 \\ -C_v & 0 \end{bmatrix} \begin{bmatrix} x_v \\ x_i \end{bmatrix} \tag{14}$$

2) LQI control with order-4 observer

The LQI control with an order-4 observer is designed with the assumption that it has one state variable which can be directly measured ($x_1(t)$) and three state variables, ($x_2(t)$, $x_3(t)$ and $x_4(t)$), are not

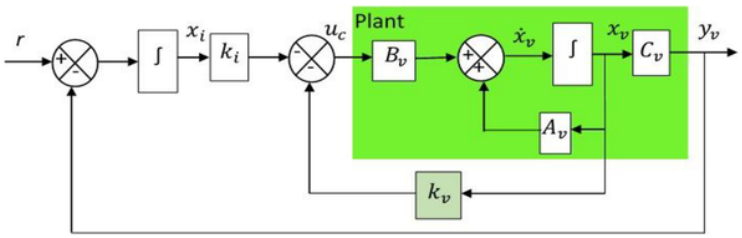


Figure 2. The LQI control design [13]

directly measurable. Figure 3 shows the LQI control system with an order-4 observer. In (7) the state variable $x_5(t)$ is dependent on the state variable $x_2(t)$. Therefore, the state variable $x_5(t)$ is ignored during observer design. Equation (7) can be expressed as follows.

$$\dot{x}_a(t) = A_a x_a(t) + F_a x_5(t) + B_a u_c(t)$$

$$y_a(t) = C_a x_a(t) \tag{15}$$

where $x_a(t) = [x_1(t) \quad x_2(t) \quad x_3(t) \quad x_4(t)]^T$,

$$A_a = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} \\ 0 & a_{32} & a_{33} & 0 \\ 0 & a_{42} & 0 & a_{44} \end{bmatrix}, F_a = \begin{bmatrix} 0 \\ a_{25} \\ 0 \\ 0 \end{bmatrix},$$

$B_a = [0 \quad b_2 \quad 0 \quad 0]^T$, and

$C_a = [c_1 \quad 0 \quad 0 \quad 0]$.

The state space equation for state variable $x_5(t)$ is given by (16).

$$\dot{x}_5(t) = A_{5a} x_a(t) + A_{5b} x_5(t) + b_5 u_c(t) \tag{16}$$

where:

$A_{5a} = [0 \quad a_{52} \quad 0 \quad 0]$,

$A_{5b} = [0]$, and

$b_5 = 0$.

State space equation of the order-4 observer is given by (17).

$$\dot{\tilde{x}}_a(t) = (A_a - L_a C_a)\tilde{x}_a(t) + F_a x_5(t) + B_a u_c(t) + L_a y_a(t) \tag{17}$$

State estimation error is given by (18).

$$e_a(t) = x_a(t) - \hat{x}_a(t) \tag{18}$$

Therefore, the following equation holds.

$$\dot{e}_a(t) = \dot{x}_a(t) - \dot{\hat{x}}_a(t) \tag{19}$$

By substituting (16) and (17) into (19), the following equation is obtained.

$$\dot{e}_a(t) = (A_a - L_a C_a)e_a(t) \tag{20}$$

The state feedback control based on the observed state $\hat{x}_a(t)$ is:

$$u_c(t) = -k_a \hat{x}_a(t) - k_b x_5 - k_i x_i(t) \tag{21}$$

By substituting (20) into (16), the following equation is obtained.

$$\dot{x}_a = (A_a - B_a k_a)x_a + (F_a - B_a k_b)x_5 + B_a k_a e_a(t) - B_a k_i x_i(t) \tag{22}$$

From (9), (20), and (22), the system using the LQI control with the order-4 observer and using the assumption that the system has a reference input, can be described by the following augmented state equation.

$$\begin{bmatrix} \dot{x}_a \\ \dot{e}_a \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A_a - B_a k_a & B_a k_a & B_a k_i \\ 0 & A_a - L_a C_a & 0 \\ -C_a & 0 & 0 \end{bmatrix} \begin{bmatrix} x_a \\ e_a \\ x_i \end{bmatrix} + \begin{bmatrix} F_a - B_a k_b \\ 0 \\ 0 \end{bmatrix} x_5 \tag{23}$$

where $\hat{x}_a(t)$ is the observer state variable, $C_1\hat{x}_a(t)$ is estimated output, $y_a(t)$ is the system output, $u_c(t)$ is control variable, and L_a is the Luenberger observer gain matrix.

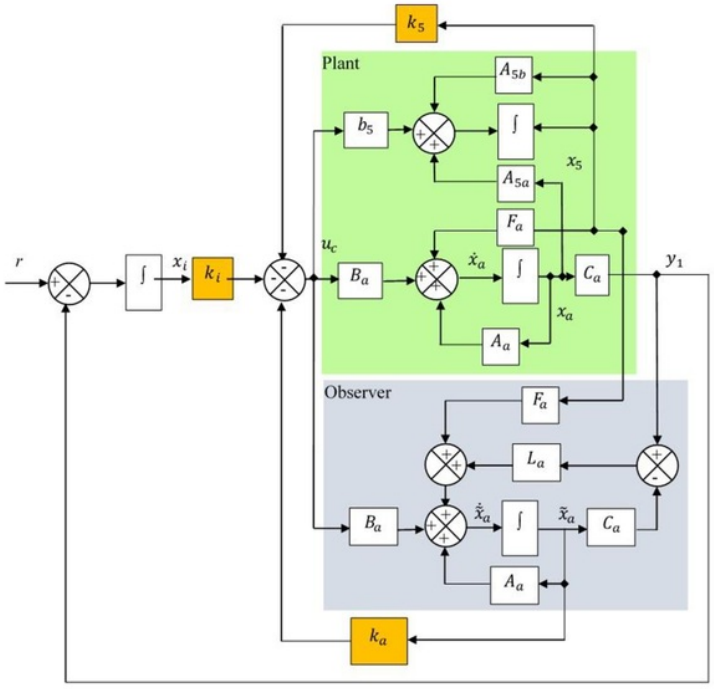


Figure 3. LQI control with order-4 observer

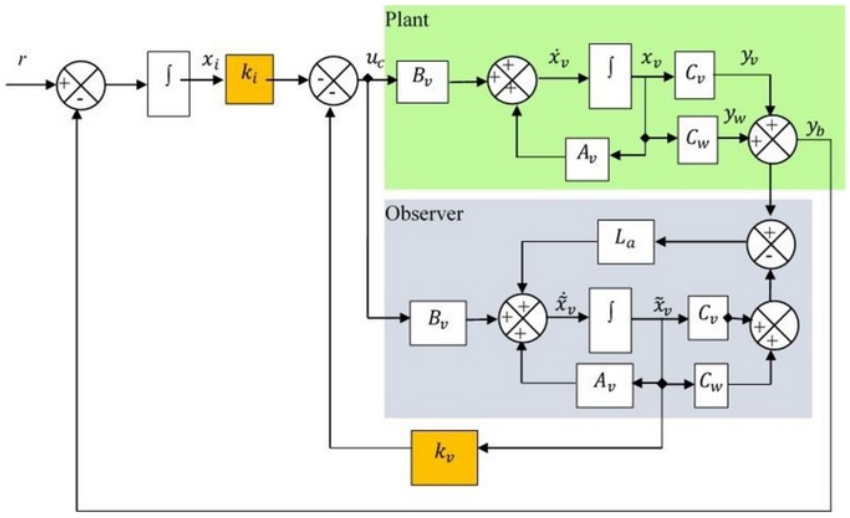


Figure 4. LQI control with order-5 observer

3) LQI control with order-5 observer

The LQI control with an order-5 observer is designed with the assumption that it has one state variable which can be directly measured ($x_1(t)$), three state variables, ($x_2(t)$, $x_3(t)$ and $x_4(t)$), are not directly measurable, and one state variable $x_5(t)$ is unobservable. Figure 4 shows the LQI control system with an order-5 observer. In (7) the state variable $x_5(t)$ is an integral of state variable $x_2(t)$. Therefore, in order to make the system be observable $x_5(t)$ is used as an additional output. Equation (7) can be expressed as follows.

$$\dot{x}_v(t) = A_v x_v(t) + B_v u_c(t)$$
$$y_b(t) = C_b x_v(t) \quad (24)$$

where:

$$x_v(t) = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5]^T,$$
$$y_b(t) = [y_v \quad y_w]^T,$$
$$x_b(t) = [x_v \quad x_5]^T,$$

$$A_v = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ 0 & a_{32} & a_{33} & 0 & 0 \\ 0 & a_{42} & 0 & a_{44} & 0 \\ 0 & a_{52} & 0 & 0 & 0 \end{bmatrix},$$

$$B_v = \begin{bmatrix} 0 \\ b_2 \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

$$C_b = [C_v \quad C_w]^T,$$
$$C_v = [c_1 \quad 0 \quad 0 \quad 0 \quad 0], \text{ and}$$
$$C_w = [0 \quad 0 \quad 0 \quad 0 \quad 1].$$

State space equation of the order-5 observer is given by:

$$\dot{\tilde{x}}_v(t) = \left(A_v - L_v(C_v + C_w)\right)\tilde{x}_v(t) + B_v u_c(t) + L_v\left(y_v(t) + y_w(t)\right) \quad (25)$$

State estimation error is given by (26).

$$e_v(t) = x_v(t) - \hat{x}_v(t) \quad (26)$$

Thus, the following equation holds.

$$\dot{e}_v(t) = \dot{x}_v(t) - \dot{\hat{x}}_v(t) \quad (27)$$

By substituting (24) and (25) into (27), the following equation is obtained.

$$\dot{e}_v(t) = \left(A_v - L_v(C_v + C_w)\right)e_v(t) \quad (28)$$

The state feedback control based on the observed state $\tilde{x}_v(t)$ is:

$$u_c(t) = -k_w \tilde{x}_v(t) - k_i x_i(t) \quad (29)$$

By substituting (29) into (24), the following equation is obtained.

$$\dot{x}_v(t) = (A_v - B_v k_w)x_v(t) - B_v k_w e_v(t) - B_v k_i x_i(t) \quad (30)$$

From (9), (28), and (30), the system using the LQI control with the order-5 observer, and using the assumption that the system has a reference input, can be described by the following augmented state equation.

$$\begin{bmatrix} \dot{x}_v \\ \dot{e}_v \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A_v - B_v k_w & B_v k_w & B_v k_i \\ 0 & A_v - L_v(C_v + C_w) & 0 \\ -(C_v + C_w) & 0 & 0 \end{bmatrix} \begin{bmatrix} x_v \\ e_v \\ x_i \end{bmatrix} \quad (31)$$

where $\hat{x}_v(t)$ is the observer state variable, $C_b\hat{x}_v(t)$ is estimated output, $y_b(t)$ is the system output, $u_c(t)$ is control variable, and L_v is the Luenberger observer gain matrix.

III. Results and discussions

A. Model parameter Molina

The model parameters were taken from an experimental electric vehicle called Molina ITB Type-3 where the specifications can be seen in Table 1. This vehicle was designed as a passenger minibus for public transport with 1500 kg weight and a wheel diameter of 58 cm. The used electric motor is a brushless DC (BLDC) electric motor with an input voltage of 48 V, 10 kW of power, 3500 rpm of motor speed rate, and 120 A of motor current. Meanwhile, the used power supply consisted of two 24 V lithium-ion batteries installed in series. Each battery had a normal capacity of 100 Ah.

B. Linearized integrated model

For 24 V input voltage, a linearized integrated model was obtained at operating point $x^{T} = [\omega_m \; i_m \; Vc_1 \; Vc_2 \; SOC_n]^{T} = [1721 \; 147.4 \; 0.15 \; 0.15 \; 99.96]^{T}$. By ignoring d_L in (7), the linearized integrated model (8) is in the following form:

$$A = \begin{bmatrix} -0.402 & 1603.77 & 0 & 0 & 0 \\ -0.019 & -3.941 & -0.003 & -0.003 & -0.0002 \\ 0 & 294.118 & -0.291 & 0 & 0 \\ 0 & 294.118 & 0 & -0.291 & 0 \\ 0 & 294.118 & 0 & 0 & 0 \end{bmatrix},$$

$B = [0 \quad 0.9871 \quad 0 \quad 0 \quad 0]^{T}$,

$C = [1.5305 \quad 0 \quad 0 \quad 0 \quad 0]$, and

$D = [0]$.

From these matrices, the poles of the open-loop system are given by -2.1710+5.3327i, -2.1710-5.3327i, -0.0001, -0.2912, -0.2907. The poles of the open-loop system can be placed at any desired location, which means that the system of the plant is stable. The system of the open-loop system is fully controllable (A_v, B_v) but it is not fully observable (A_v, C_v), where the system has an observability rank of four. It means that the system has one state variable that is not observable, i.e. SOCn, but the system is detectable.

C. Cases of control design

The various cases of the LQI control design were as follows:

1) Case 1: LQI control

The LQI control system is based on (9), the augmented state equation is given by (11), the performance index is using (13), the gain full state feedback is given by K_v = [0.0234 5.6992 0.0008 0.0008 0.0015], and the gain integral is expressed in K_i = [-0.0316]. The weighting matrices of the LQI are chosen based on trial and error approach. In order to obtain the optimum state feedback control gains, the weighting matrices were selected as follows: Q = diag[0.1], and R = 100.

A gain of state feedback that is defined by the eigenvalues of the system is necessarily needed to solve the problem. The eigenvalues of the closed-loop system in (14) are given as $-4.884 + 7.007i$, $-4.884 - 7.007i$, $0.224 + 0.104i$, $-0.224 - 0.104i$, -0.044, and 0.291.

Table 1.
Parameter of Molina ITB Type-3

Specifications	Symbol	Value	Units
Motor BLDC			
Resistance	R_m	12.4	mΩ
Inductance	L_m	34	uH
Torque constant	K_t	0.1082	Nm/A
Inertia	J_m	48×10^{-6}	kgm^2
Stiffness	b_m	79×10^{-4}	Nms/rad
B_{mf} constant	K_e	0.0128	Vs/rad
Lithium-ion battery			
Inner resistance		2	mΩ
Terminal resistance,	R_t	1.72	mΩ
Terminal capacitance,	C_t	2000	F
n-capacity,	Q_n	100	Ah
Vehicle			
Mass,	m_v	1500	kg
Wheel radius,	r_w	0.29	m
Wheel inertia,	J_w	12×10^{-6}	kgm^2
Transmission Inertia,	Jt	53×10^{-6}	kgm^2
Air density,	ρ	1.25	kg/m^3
Drag coefficient,	C_d	0.417	Ns^2/kgm
Frontal area,	A_f	1.581	m^2
Rolling coefficient,	C_{rx}	0.015	
Gravity coefficient,	g	9.8	m/s^2

2) Case 2: LQI control with order-4 observer

To provide a solution for Case 2, the partition state variables can be obtained using (15). The matrices are given as:

$$A_a = \begin{bmatrix} -0.402 & 1603.77 & 0 & 0 \\ -0.019 & -3.941 & -0.003 & -0.003 \\ 0 & 294.118 & -0.291 & 0 \\ 0 & 294.118 & 0 & -0.291 \end{bmatrix},$$

$$F_a = \begin{bmatrix} 0 \\ -0.0002 \\ 0 \\ 0 \end{bmatrix},$$

$$B_a = \begin{bmatrix} 0 \\ 0.987 \\ 0 \\ 0 \end{bmatrix},$$

$C_a = [1.531 \quad 0 \quad 0 \quad 0]^T$,

$k_a = [0.023 \quad 5.699 \quad 0.0008 \quad 0.0008]$,

$k_5 = [-0.0316]$,

$k_i = [-0.0316]$, and

$L_a = [-0.4180 \quad -0.0126 \quad -0.330 \quad -0.330]^T$.

Based on (23), the eigenvalues of the closed-loop system are given as -1.804+9.754i, -1.804-9.754i, -0.782, -0.289, -0.291, -2.168+5.391, -2.168-5.391, -0.297, and -0.291.

3) Case 3: LQI control with order-5 observer

To provide a solution for Case 3, the partition state variables can be obtained using (24). The matrices are given by as:

$$A_v = \begin{bmatrix} -0.402 & 1603.77 & 0 & 0 & 0 \\ -0.019 & -3.941 & -0.003 & -0.003 & -0.002 \\ 0 & 294.118 & -0.291 & 0 & 0 \\ 0 & 294.118 & 0 & -0.291 & 0 \\ 0 & 294.118 & 0 & 0 & 0 \end{bmatrix},$$

$B_v = [0 \quad 0.9871 \quad 0 \quad 0 \quad 0]^T$,

$C_v = [1.5305 \quad 0 \quad 0 \quad 0 \quad 0]$,

$C_w = [0 \quad 0 \quad 0 \quad 0 \quad 1]$,

$K_w = [0.0234 \quad 5.699 \quad 0.0008 \quad 0.0008 \quad 0.0015]$,

$K_i = [-0.0423]$, and

$L_w = [-0.008 \quad -0.003 \quad -0.007 \quad -0.007 \quad -0.003]^T$.

Based on (36), the poles or eigenvalues of the closed-loop system are given as -4.944+6.941i, -4.944-6.941i, -0.0393+0.042i, -0.0.393-0.042i, -0.292, -2.164+5.265i, -2.164-5.265i, -0.002, -0.292, -0.291 and -0.291.

All the eigenvalues of the closed-loop system and the observers must be negative. Theoretically, these eigenvalues can be arbitrarily moved to minus infinity to achieve extremely fast convergence. The problem of selecting good eigenvalues is not easily solved. However, the observer may be slightly faster than the rest of the closed-loop system.

Generally, the formula is defined with 2 to 6 times larger poles for the observer than for the closed-loop systems' poles. This can increase the noise on the observer side. In this case, the poles were set 5 times larger for the observer than for the closed-loop system. This means that the observer may be slightly faster than the closed-loop system and the observation error decays shortly to zero.

Initial condition values influence the state variables values forward through time. In other words, the state variables are a function of time and the initial condition values. The initial state variables values were selected as $x(0) = [1\ 0\ 0\ 0\ 0]^T$.

Based on Figure 5, in which the response to state variables versus time is shown, all state variables were defined. The state variables were: $x_1 = \omega_m$, $x_2 = i_m$, $x_3 = V_{c1}$, $x_4 = V_{c2}$, $x_5 = SOC_n$, and x_i is the integral state. For all cases of the control design, it can be seen that the motor speed response (x_1) and the motor current response (x_2) were the same, whereas x_3, x_4, x_5 and x_i had a different response. It can be seen that x_3 and x_4 had the same response in Case 1 (red line) and Case 3 (black line), and reached steady state after 3 seconds, so that Case 2 (green line) reached steady state after 4 seconds.

Also, x_i was the same in Case 1 and Case 2, and reached steady state after 6 seconds. This was also the case in Case 3, reaching a steady state after 1 seconds, which means faster than Case 1 and Case 2 by around 5 seconds. However, for x_5, Case 2 had undershoot, while it reached steady state in the same time as Case 2, i.e., after 6 seconds. Case 3 had the best response, reaching a steady state after 2.6 seconds. This means that Case 3 had unexploited battery energy.

To obtain the response of the observer error vector to the following initial observer error $e(0) = [1\ 0\ 0\ 0]^T$. The response to state estimate versus time with the initial observer error is shown in Figure 6. The error was happened just for Case 2 and Case 3, while there is no error for Case 1 because Case 1 is designed without any observer. The state estimate in Case 2 (red line) was $e_1 = \tilde{\omega}_m$, $e_2 = \tilde{\imath}_m$, $e_3 = \tilde{V}_{c1}$, and $e_4 = \tilde{V}_{c2}$. In Case 3 (blue line) it was $e_1 = \tilde{\omega}_m$, $e_2 = \tilde{\imath}_m$, $e_3 = \tilde{V}_{c1}$, and $e_4 = \tilde{V}_{c2}$ and $e_5 = \widetilde{SOC}_n$.

The response of Case 3 is the fastest, which means that the observer has the same structure as the system, with a feedback driving term where the observation error decays shortly to zero. This means that Case 3 had the best observer error response.

D. Energy consumption

The purpose of this simulation was to see how the use of a BEV model combined with the observer in the speed control design influences the energy consumption of the electric vehicle. An electric vehicle was simulated using a small-scale simulator, and the energy usage for a certain driving profile was presented in [14].

In this part of work, the energy consumption can be observed in two ways. First, the vehicle moves on a flat surface with a constant vehicle speed of 60 km/h in the

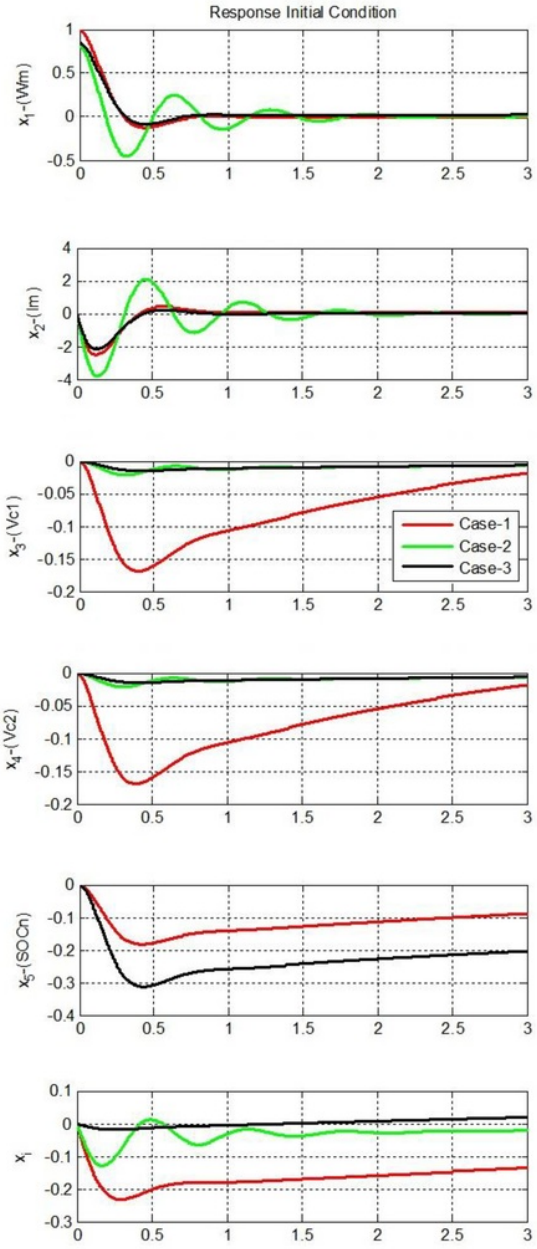


Figure 5. Initial condition response (state variable versus time)

simulation, and second, a simulation was performed according to the standard NEDC (a new European driving cycle) driving profile. The NEDC is a test procedure as long as the vehicle moves at a speed profile. The speed profile has a major impact on the resulting energy consumption [15].

The formulation of the various performance index to observe the energy consumption was based on the following characteristics:

- Control energy

  $E_1 = \int_0^\infty V_m(t)^2\, dt$ or $J_1 = \int_0^\infty {u_c}^2\, dt$

- Mechanical energy

  $E_2 = \int_0^\infty T_m(t)\omega_m(t)\, dt$ or $J_2 = \int_0^\infty x_2 x_1\, dt$

- Motor energy input

  $E_3 = \int_0^\infty V_m(t) I_m(t)\, dt$ or $J_3 = \int_0^\infty u_c x_2\, dt$

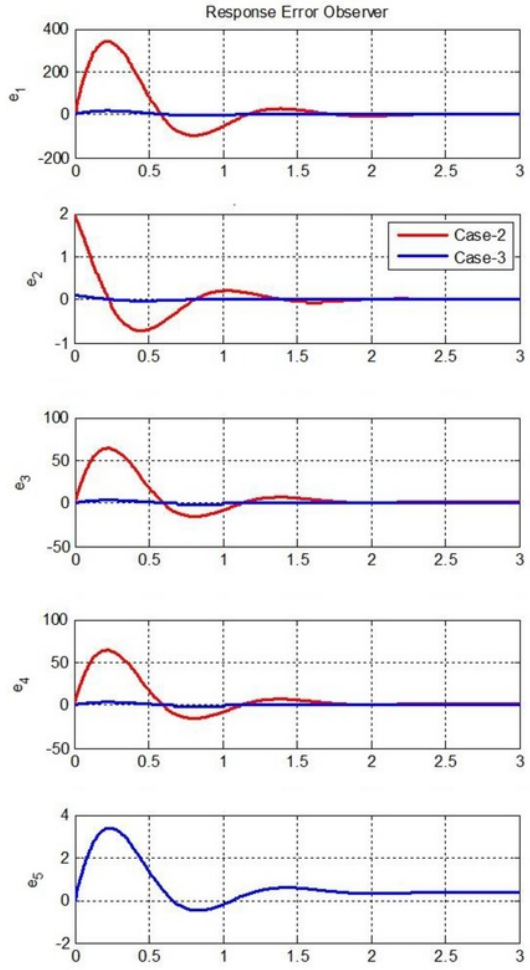


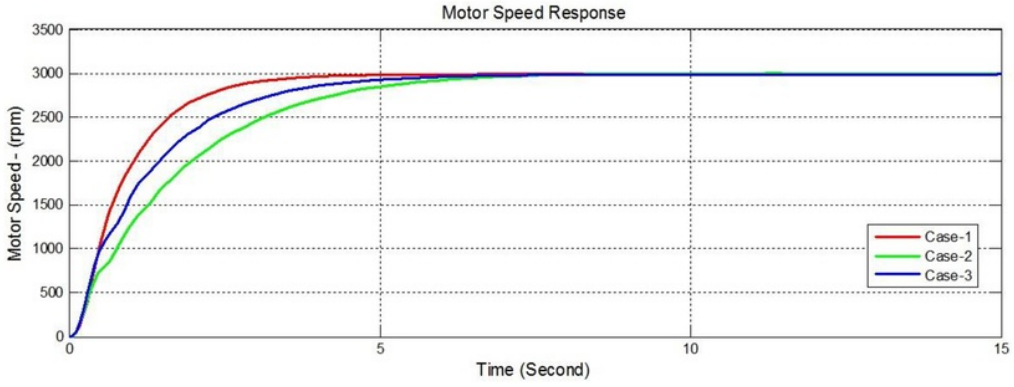
Figure 6. The error of observer response (state observer versus time)

1) Constant vehicle speed

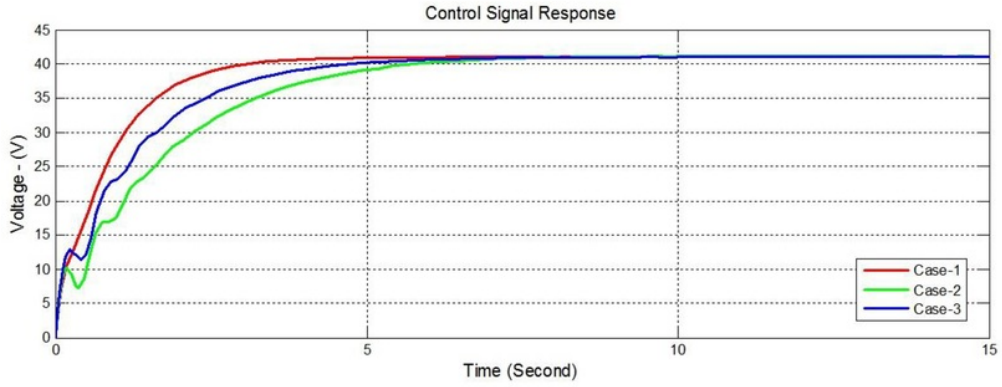
In the simulation, the vehicle was moving on a flat surface with a constant speed at 60 km/h for 15 seconds duration. In Figure 7, it was shown that the motor speed reached 3000 rpm, and control signal about 41 V with the same response for all cases. However, it was also shown that all three cases had different time settling. In Case 1, it was a faster settling time, while in Case 2, it was a slower settling time. The response of the motor current showed the same transient response. This means that if the motor current has different values for reaching 3000 rpm or 60 km/h, it has an effect on energy consumption. The energy consumption was presented by J_1, J_2, and J_3.

Table 2.
Energy consumption

State feedback	Energy consumption (Watt-hour)		
	J_1	J_2	J_3
Constant Vehicle Speed at 60 km/h (during 15 seconds)			
Case 1	0.798×10^3	2.205×10^3	2.796×10^3
Case 2	0.701×10^3	1.944×10^3	2.465×10^3
Case 3	0.626×10^3	1.732×10^3	2.196×10^3
NEDC Profile (during 1200 seconds)			
Case 1	1.223×10^3	5.025×10^3	6.369×10^3
Case 2	1.061×10^3	4.396×10^3	5.528×10^3
Case 3	0.964×10^3	3.964×10^3	5.020×10^3



(a)



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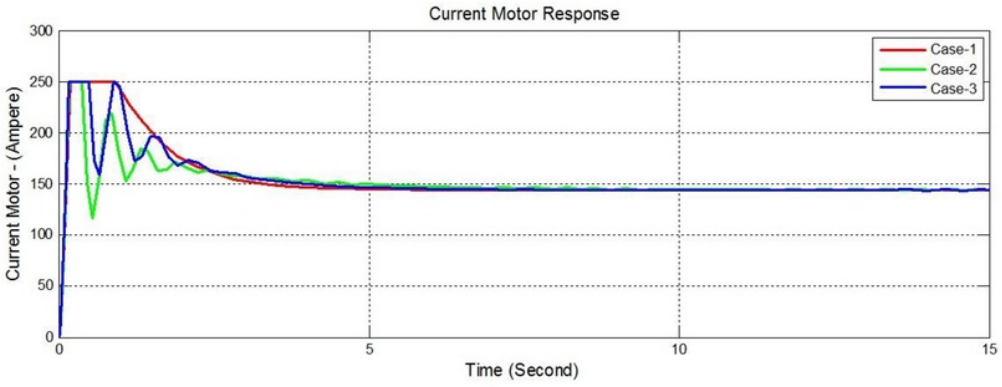

(c)

Figure 7. Response system when the vehicle moved; (a) motor speed response; (b) control signal response; (c) current response

In Table 2, it was shown that the energy consumption in Case 3 was 27.45% (J_1), 27.27% (J_2), and 27.34% (J_3) better than in Case 2. The energy consumption in Case 3 also showed 12.04%, 12.21% and 12.24%, for J_1, J_2, and J_3 respectively, which were better than in Case 1. This result means that the energy consumption in Case 3 was the most efficient out of these three cases.

2) NEDC driving profile

A simulation was performed on the moving vehicle according to the NEDC driving profile for 1200 seconds. The simulation result can be seen in Table 2 where the energy consumption for the vehicle using NEDC profile in Case 3 was 21.17% (J_1), 21.12% (J_2) and 21.18% (J_3) better than in Case 2. The energy consumption in Case 3 also showed 10.04%, 10.09%

and 10.12% better than in Case 1 for J_1, J_2, and J_3 respectively. This result means that the energy consumption in Case 3 is the most efficient out of these three cases.

IV. Conclusion

Optimal speed control with observer applied to an integrated battery-electric vehicle (IBEV) model was presented. An LQI control design was used for the feedback control design, and a Luenberger observer was used to design the observer. In the design of the observer, it was assumed that there was one indirectly measurable and unobservable state variable in the system that was used to build the LQI control with order-5 observer. For comparison, an LQI control only and an LQI control with order-4 observer were also designed. All control design cases simulated a vehicle moving on a flat surface and moving according to the NEDC driving profile. The LQI control with order-5 observer (Case 3) provided the highest energy efficiency. Moreover, the transient response in Case 3 was slightly faster than in Case 2. An optimal speed control design with observer was shown to have the potential to provide higher energy efficiency for integrated battery-electric vehicles. Its application is currently under further research.

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References

[1] A. G. Boulanger, A. C. Chu, S. Maxx, and D. L. Waltz, "Vehicle Electrification: Status and Issues," *Proceeding of the IEEE*, vol. 99, no. 6, pp. 1116–1138, Jun. 2011.

[2] Q. Wang and M. Deluchi, "Impacts of electric vehicles on primary energy consumption and petroleum displacement," *Energy*, vol. 17, no. 4, pp. 351–366, Apr. 1992.

[3] R. Ristiana, A. S. Rohman, A. Purwadi, and C. Machbub, "Energy efficient torque control using integrated battery-electric vehicle model," in *Proceeding of 2017 7th IEEE International Conference on System Engineering and Technology (ICSET)*, 2017, pp. 223–228.

[4] R. Ristiana, A. S. Rohman, A. Purwadi, and C. Machbub, "Integrated battery-electric vehicle model and its optimal speed control application," in *Proceeding of 2017 3rd International Conference on Control, Automation and Robotics (ICCAR)*, 2017, pp. 588–592.

[5] R. Ristiana, H. Hindersah, A. S. Rohman, C. Machbub, A. Purwadi, and E. Rijanto, "Torque control using integrated battery-electric vehicle model with flexible shaft," in *Proceeding of 2017 4th International Conference on Electric Vehicular Technology (ICEVT)*, 2017, pp. 24–29.

[6] J. O'Reilly, *Observers of Linear System*, London: Academic Press, 1983.

[7] R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*. Boston, MA: Springer US, 2001.

[8] C.-L. Xia, *Permanent Magnet Brushless DC Motor Drives and Controls*. Singapore: John Wiley & Sons Singapore Pte. Ltd., 2012.

[9] T. D. Gillespie, *Fundamentals of Vehicle Dynamics*. Warrendale, PA: SAE International, 1992.

[10] G. L. Plett, "*Modelling, Simulation and Identification of Battery Dynamics,*" Wiley, 2014.

[11] M. Oswal, J. Paul, and R. Zhao, "*A Comparative Study of Lithium Ion Batteries*," University of Southern California, 2010.

[12] R. D. Martino, "*Modelling and Simulation of The Dynamic Behavior of The Automobile*," Thesis of Degree, Faculty of Engineering, Universita Degli Studi at Salerno, 2005.

[13] U. Kiencke and L. Nielsen, *Automotive Control Systems*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005.

[14] A. R. Al Tahtawi and A. S. Rohman, "Simple supercapacitor charging scheme of an electric vehicle on small-scale hardware simulator: a prototype development for education purpose," *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, vol. 7, no. 2, p. 77, Dec. 2016.

[15] E. C. J. R. Centre, *Regulated Emissions of a Euro 5 Passenger Car Measured Over Different Driving Cycles*, Institute for Environment and Sustainability, 2010.

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