International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE
ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com
September 2013 | Issue 16 | Volume 5 | Number 3 | Pages 126-132

MIXED H_2/H_∞ APPROACH TO DETECT FAULT IN PARALLEL HYBRID ELECTRIC VEHICLE

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Abstract- In this paper a parallel Hybrid Electric Vehicle (HEV) is simulated based on the faulty condition. A dynamic output feedback robust Fault detection technique is used to evaluate the faulty condition when the miss-operation cause that the output torque of parallel HEV, has been disturbed. This paper presents the fault detection method based on the mixed H_2/H_∞ approach, if the measuring signals are faulty. The simulation are based on the systems state space Model and then transferring it to Linear Matrix Inequality (LMI) to obtain the sub-optimal problem solution.

Keywords: Fault Detection, Mixed H_2/H_∞, Parallel Hybrid Electric Vehicle (HEV), Torque Control.

I. INTRODUCTION

The widespread growth of the purely electric and Hybrid Electric Vehicles (HEV) due to restricted pollution and high efficiency of such drive trains compared with conventional Internal Combustion Engines (ICE); exhibits a new branch in vehicle engineering. The concept of hybrid electric vehicle is introduced to overcome disadvantages of the ICE engines, like poor fuel economy, pollution aspects and inefficient braking performance. This matter is solved by using an electric motor to both traction and regenerative braking aspects which can increasingly improve the torque and power characteristic of the vehicle. Among the variety configurations of the Hybrid Electric Vehicle, the one that are considered in this paper is parallel HEV.

Because of the complexity of such a system, containing mechanical and electrical sub systems and the interaction between them, a robust control unit with precise fault detection system is unavoidable. Various parts such as an ICE, Electric Motor Drive, braking system, energy management unit, Peak power source [2], require a self controller or at least a monitoring system, which can control by a central control unit.

During past years there were many works on HEV control system, but a few ones are in the field of fault detection. In [4] a neural network controller for improved fuel efficiency of the Toyota Prius hybrid electric vehicle is proposed, that contains a battery fault detector unit. In [5] a reconfigured electric drive is used, which introduces a new topology containing a prevalent drive and some other switches to reconfigure the drive system after a pulse mismatch fault in drive switches. Paper [6] describes active fault-tolerant control systems for a high performance induction-motor drive that propels an electrical vehicle (EV) or a hybrid one (HEV). The fault tolerant control systems adaptively reorganize themselves in the event of sensor loss or sensor recovery to sustain the best control performance, given the complement of remaining sensors.

But the base of the controller is on the fuzzy system which dependency of the controller to signals is unavoidable. Paper [7] represents an observer-based analytical redundancy for a steer-by-wire (SBW) system. An analytical redundancy methodology was utilized to reduce the total number of redundant road-wheel angle (RWA) sensors. Paper [8] presents a fault-tolerant control approach for four-wheel independently driven (4WID) electric vehicles. An adaptive control-based passive fault-tolerant controller is designed to ensure vehicle system stability and to track the desired vehicle motion when an in-wheel motor/motor driver fault happens. In [9] the studies of lateral and longitudinal path tracking control of four-wheel steering autonomous vehicles are done based on virtual point fault tolerant.

In [3] a novel control strategy of torque ripple reduction in hybrid electric vehicles (HEVs) is represented that is the case study system in this paper. By the periodic cycle of power production, the internal combustion engine used in a hybrid vehicle provides a torque that fluctuates constantly, and these fluctuations increase by reduction in cylinder number of the engine. In [3] the proposed control system is based on H_∞ strategy, which reduces the pulsation torque of ICE using a permanent magnet synchronous machine (PMSM) and control feedback signals of shaft speed and torque. The mentioned article shows that the importance of torque and speed measuring is in high degree.

Therefore in this paper the fault detection method for parallel hybrid electric vehicle is proposed to determine whether the system internal fault occurs or not. To do this an H_2/H_∞ approach that is introduced in [1] is included in the system. The method is on the base of system's state space model. Therefore after deriving the ICE and PMSM model, the problem is converted to Linear Matrix Inequality problem that can be solved using LMI block set in MATLAB-SIMULINK. After solving problem, the Kalman filter gain will be available to detect faulty condition.

II. HYBRID ELECTRIC VEHICLE

A hybrid electric vehicle consist of two power source, the main power source is an ICE, and the other power source which can called Peak Power Source (PPS), may be a battery pack, ultra capacitor, flywheel or the combination of these sources. In references there were almost two main categories of these types of vehicles. The first one is series HEV and the other is parallel HEV.

In series Hybrid Electric Vehicle as shown in Figure 1, the internal combustion engine is connected to electric generator shaft and the output terminals of the generator is connected to a DC bus through a controlled AC/DC converter. The battery pack is also connected to the DC bus through a bidirectional buck/boost DC/DC converter. The electric motor which propels the vehicle is connected to drive wheels through transmission system and controlled by electric drive connected to DC bus. The main advantage of this type of HEV is the mechanical isolation of the ICE from the vehicle wheels which lets the ICE to work at its most efficient area on torque-speed profile.

The other configuration is parallel HEV. The ICE and electric power source are connected as parallel that depicted in Figure 2. Torque and/or speed of the ICE and electric motor can add to each other through a set of planetary gear and/or belt system to couple the speed or torque of two power source. In some configurations both of the speed and torque can be coupled at the same time. This configuration has the advantage of high torque profile and also the small size in electric motor rating. The other advantage compared to series configuration is its high efficiency that cause by disappearing of multiple power conversion (mechanical to electrical and again to mechanical).

In some literatures [2], by using a series-parallel configuration, it will be available to reach the advantages of both configurations that is called series-parallel or complex hybrid electric vehicle.

The electric motors due to their torque and power characteristic, that is proper in vehicular applications are widely used in electric traction systems, such as Induction motors, Permanent Magnet Brushless Synchronous Machines, Switch Reluctance Machines and DC Motors. All of these machines are need to be controlled through a drive system with various pulse type and operating algorithms such as PWM controller, SVM, Vector control, sensor less or Field Oriented Control.

In most of these control strategies there were requirements of system parameters that should be measured, such as vehicle speed, ICE and electric motor angular speed and output torque, state of charge of PPS, braking parameters, throttle position, DC Bus voltage and so on. The miss operation of sensing devices can cause the malfunction of the control system which resulting drive train to operate in undesirable way.

The other condition that may cause faulty operation is due to internal malfunction of any system parts such as ICE, electric motor, vehicle controller, braking system, and steering unit. Therefore a robust fault detecting system may be required to identify any faulty condition.

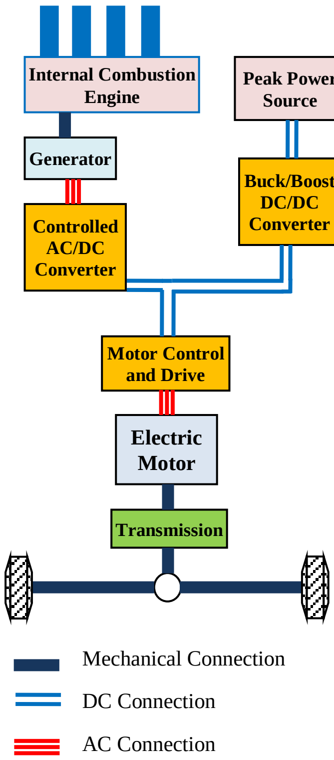

Figure 1. Series connection Hybrid Electric Vehicle

III. PROBLEM STATEMENT

A. Problem Formulation

As it mentioned in reference [2], the system dynamic is described by LTI system.

$$G:\begin{cases} x' = Ax + B_1u + B_2v + B_3w + B_4f \\ y = Cx + D_1u + D_2v + D_3w + D_4f \end{cases} \quad x(0) = x_0 \qquad (1)$$

where, $x \in \Re^n$ is the state vector, $u \in \Re^m$ is the known input and $y \in \Re^p$ is output vector. The unknown input $w \in \Re^1$ is assumed as fixed spectral density noise which can affect the process or measurement and the unknown input $v \in \Re^r$ is assumed as finite energy disturbance modeling error due to exogenous signal, linearization or parameter uncertainty. The other unknown input $f \in \Re^q$ is a possible fault. The matrices A_i, B_i, C_i and D_i are the known constant matrices.

The weight function that reflecting the knowledge of where w and v are assumed to be absorbed due to Equation (1). The pair (C, A) is assumed to be detectable and D_3 has full rank.As mentioned in [1], the objective of fault detection design is to construct the residual generator like V which takes$u$ and y as inputs then generate the residual signal v to decide whether or not the fault$f$ has occurred in the system G. The occurrence of f depends on some conditions if the norm of v is larger than a known threshold, or there is a sudden change in its statistical properties.

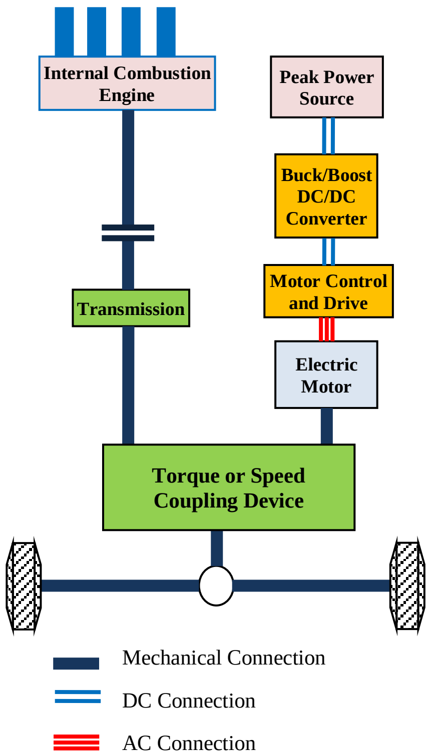

Figure 2. Parallel connection Hybrid Electric Vehicle

Considering remark 3.1 in [1], by labeling the specific fault to be located at f and combining the remaining faults in the unknown disturbance v, a dedicated residual generator V can be designed. Considering V as a finite dimensional system of nth order Kalman-Luenberger filters:

$$V:\begin{cases} \hat{x}' = A\hat{x} + B_1 u + K(y - D_1 u - C\hat{x}) \\ v = y - D_1 u - C\hat{x} \end{cases} \quad \hat{x}(0) = \hat{x}_0 \qquad (2)$$

To generate V it's necessary to find the gain matrix K. Using Equations (1) and (2) as mentioned in [1], the error dynamic can be written:

$$T:\begin{cases} e' = Ax + B_2 v + B_3 w + B_4 f \\ y = Ce + D_2 v + D_3 w + D_4 f \end{cases} \quad e(0) = e_0 \qquad (3)$$

In this equation $e = x - \hat{x}$ is the error signal of states, $A_i = A - KC$ and $B_i = B - KD_i$. The vector v is completely decoupled from input u. By using Equation (3), the residual v can express as $v = \bar{v} + v_0$ where:

$$\bar{v} = T_1 e_0 + T_2 v + T_3 w + T_4 f \quad , v_0 = D_3 w \qquad (4)$$

where,

$$T_1 := (A, I_n, C, 0)\,, \quad T_2 := (A, B_2, C, D_2)$$
$$T_3 := (A, B_3, C, 0)\,, \quad T_4 := (A, B_4, C, D_4) \qquad (5)$$

The vector v_0 is independent of filter gain K and depend only on w, also if $K \in \Omega$, then $T_i \in \Re H_\infty$.

As mentioned in remark 3.2 in [2], $\| T_3 \|_2$ is finite, and in fault free case the v, will be asymptotically white. Because that v is proposed to decide about the occurrence of fault, therefore it is desired that v be insensitive to unknown input and initial conditions. So transfer function from v and w to v should be attenuated. Therefore according to [1] minimization problem will be as below:

Assume v and w, are white noises and $D_2 = 0$, finding the gain K which satisfies:

$$\min_{K \in \Omega} \|(T_2 T_3)\|_2 \qquad (6)$$

Assume v and w, are $\Im_2$ functions. With $\gamma > 0$, find the gain K, which solve the:

$$\|(T_2 T_3)\|_\infty < \gamma \qquad (7)$$

These problems are H_2 (Kalman Filter) and H_∞ filtering problems. According to [1], these two problems can mixed to each other, to form a mixed H_2 / H_∞ residual generating problem. That mentioned in [1] as problem 3.3:

Assume v is a $\Im_2$ function and w, is white noises process. With $\gamma > 0$, find the gain K, which solve the:

$$\min_{K \in \Omega} \{ \|T_3\|_2^2 : \|T_2\|_\infty < \gamma \} \qquad (8)$$

In literatures, the solution of this problem is not known except in special situations. Therefore to overcome this difficulty, the method mentioned in [1] is used, that replaces the $\| T_3 \|_2$ by H_2 upper bound, making it possible to achieve an optimal upper bound for $\| T_3 \|_2$, which lead us to construct a method for mixed H_2 / H_∞ residual generator.

B. Mixed H_2 / H_∞ Residual Generator

In Equation (8), let the $\gamma > 0$ is given, then by the procedure in [1], then the mentioned problem can be converted to set of Linear Matrix Inequalities (LMI) as below:

$$\min_{Q,Z,U} \mathrm{Tr}[Z]$$

$$\begin{pmatrix} Z & B_3^T Q - D_3^T U^T \\ QB_3 - QD_3 & Q \end{pmatrix} \geq 0$$

$$\begin{pmatrix} A^T Q + QA - C^T U^T - UC & QB_2 & C^T \\ B_2^T Q & -\gamma^2 I & 0 \\ C & 0 & -I \end{pmatrix} \geq 0 \qquad (9)$$

$$Z = Z^T \geq 0$$

$$Q = Q^T > 0$$

Considering Equation set (9), the following algorithm [1] can used to generate mixed H_2 / H_∞ residual.

Given the data $(A, B_2, B_3, C, D_2, D_3)$, design the residual generator *V*, by the below procedure:

- Step 1. Initialize $\gamma > 0$.
- Step 2. Solve Problem 9 to obtain $\hat{Q}$ and *U*. If the convex minimization problem is not feasible, increase γ to make the problem feasible, otherwise continue.
- Step 3. Compute the gain *K*, using $K = \hat{Q}^{-1}U$, and construct the residual generator *V*, in Equation (2).

IV. CASE STUDY AND MODELING

Our case study is a parallel HEV in reference [3], which is composed of an ICE and a PMSM motor. These two sources are coupled with pulley and belt device, with torque ratio 2. As mentioned in section III, the parallel HEV, consist of two parallel torque sources, first is an ICE fueled with fossil base and the second is an electric motor fueled with battery pack (or ultra capacitor or flywheel) which combine to each other at the torque coupling device. Each of these sources can propel the vehicle independently.

The PMSM is a 15 KW motor with capability to produce 64 [N.m] as nominal torque that has 5 pole pair. The motor coupled to engine due to belt system with ability to couple 70 KW power. The ICE is capable to produce 80 [N.m] torque at angular speed of 2000 rpm.

The state space representation of ICE in dynamic equations is as below [3]:

$$\theta'_{ICE} = \omega_{ICE}$$
$$J_{ICE}\omega'_{ICE} = k\left(\frac{\theta_{el}}{n} - \theta_{ICE}\right) + c\left(\frac{\omega_{el}}{n} - \omega_{ICE}\right) + T_p - T_l \quad (10)$$

The PMSM motors dynamic equations can be written as below that mentioned in [3]:

$$\frac{di_d}{dt} = -\frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_{el} i_q + \frac{1}{L_d} v_d$$
$$\frac{di_q}{dt} = -\frac{R}{L_q} i_q + \frac{L_d}{L_q} p\omega_{el} i_d + \frac{1}{L_q} v_q - \frac{\lambda}{L_q} p\omega_{el} \quad (11)$$
$$\theta'_{el} = \omega_{el}$$
$$J_{el}\omega'_{el} = k\left(\frac{\theta_{ICE}}{n} - \frac{\theta_{el}}{4}\right) + c\left(\frac{\omega_{ICE}}{n} - \frac{\omega_{el}}{4}\right) + T_{em}$$

Combining Equations (10) and (11), and using real and imaginary parts of the above parameters, we can obtain the state space representation of the system dynamic as Equation (12):

$$\begin{cases} x' = Ax + B_1(u+f) + B_2 v + B_3 w \\ y = Cx + D_1(u+f) + D_2 v + D_3 w \end{cases} \quad (12)$$

where the vector *x* is system estimated state vector, *u*+*f* is the combination vector of inputs and fault, the input vector *u* is composed of real and imaginary parts of the stator q component current. The exogenous input vector *v* is formed using torque perturbation in real and imaginary axis, and the vector *w* is the disturbance in the system dynamic. All of these vectors and matrices are shown in Appendix.

V. FAULT NATURE

The mentioned method in section IV is capable to detect the system internal faults, by the vector *v* in Equation (2). These faults can be occurred in various conditions due to vehicles operating condition and its internal systems performance such as:

- Mismatch operation of PMSM drive system during switches pulse mismatch. This phenomena causes that the applied voltage to stator missed in some cases, that cause a sudden change in torque of electric motor.
- Incur of stroke to PMSM motor. This condition causes impact in the magnetization property of motors permanent magnets. Such a condition can be occurred in vehicles that are running in bumpy roads or countryside. The effect of such a fault may produce unwanted downfall in motors torque.
- The faulty condition in ICE operation like flywheel system a centric operation due to slat, which cause pulsation in the engine produced torque.
- Ripple torque due to low angular speed operation of ICE that can be detected by this method and feed the central control system to decide to switch to purely electric propelling mode.

All of the mentioned faults is due to system nature and are categorized in internal fault group. These faults can affect the produced torque that is the decision factor in this paper. To find the faulty condition, we should, observe vector *v* then if the signal has the high value in some time intervals, then fault would happen in system.

VI. RESULTS

To show the mentioned fault detection method, works properly, using Equation set (12) and by calculating the proper γ value, with the algorithm in section IV, the gain of Kalman filter can be achieved. The proper $\gamma = 0.0000023$, is capable to detect the faulty condition. The applied pulse type disturbance and fault with random white noise with unit power spectrum $(v \sim N(0,1))$ are shown in Figure 3. These functions are system inputs as mentioned in Equation (12), by *w*, *f* and *v*, respectively.

The fault detector signal *v*, that decide the faulty condition are shown in Figure 4, for the inputs of Figure 3. It is obvious that the weight of the fault signal is greater than other signals, which reflect the effect of fault in the *v* signal. Because of the MIMO system we have two residual signals.

The role of LMI problem solution, is very important to detect the fault occurrence, by varying the value of γ to grate amount that mentioned, causes decrease in the weight of fault signal comparing with disturbance and noise, for example with $\gamma = 0.00023$, the residual signal are depicted in Figure 5, as it is obvious the effect of the noise is comparative due to fault amount. It causes difficulty in the identification of the fault.

If the value of γ increase some more, the detection process will be impossible, the results for such a γ value, are shown in Figure 6, that the weight factor of the fault decrease too much, therefore noise and disturbance signals effect in residual signal will be grow too much.

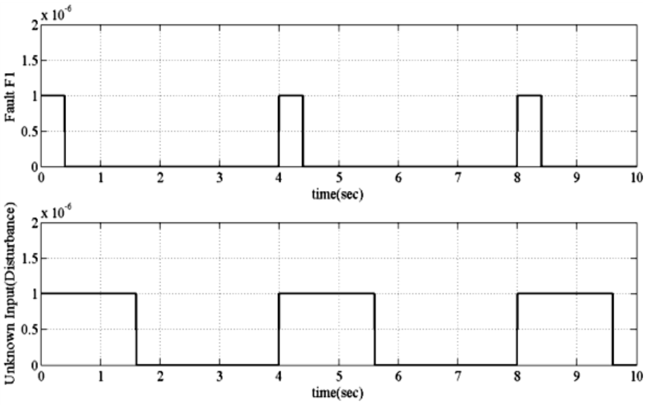

Figure 3. The fault input (up) and the disturbance (bottom) signals used in model

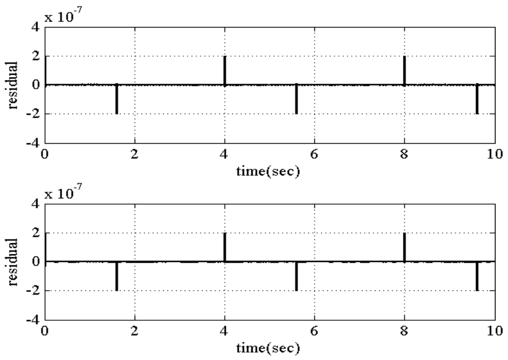

Figure 4. Two residual signal with proper value of $\gamma = 0.0000023$, that represent the fault occurrence due to Figure 3

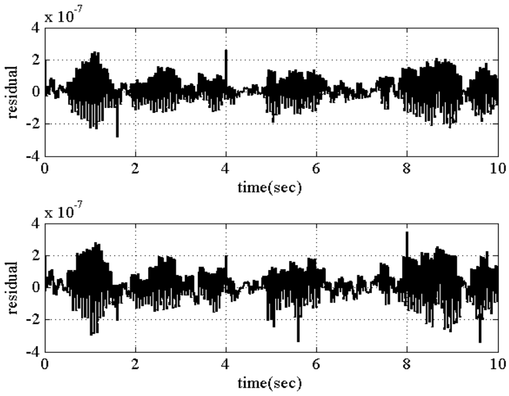

Figure 5. Two residual signal with improper value of $\gamma = 0.00023$, the fault occurrence is difficult to detected

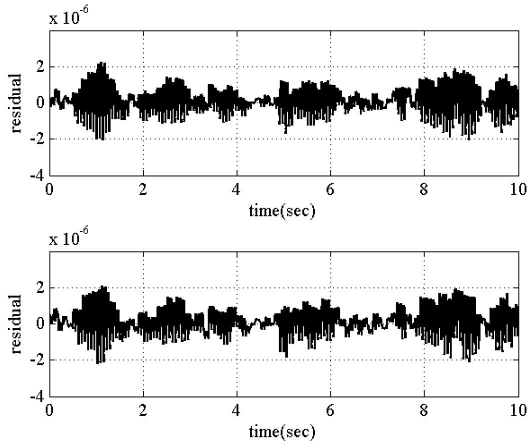

Figure6. Two residual signal with improper value of $\gamma = 0.00023$, the fault occurrence is impossible to detected

VII. CONCLUSIONS

The fault happening in physical systems is unavoidable; therefore in modern systems with many different parts, that work together to reach the same goal, a proper fault detection method should be used to overcome the malfunctions, cause by a miss operation of system. During past years various, methods of fault detecting has been introduced. The one method that is the base idea of this work is the fault detection method in present of unknown inputs. In this method the residual signal, produced by fault detector filter, contains the effect of both unknown input and fault. There were also presented a lot of methods to reduce the effect of unknown input and increase the effect of fault. Among these methods it has been shown in this paper that the mixed H_2/H_∞ approach is the proper method to detect the faulty condition in parallel hybrid electric vehicle. In this method the suboptimal problem that contains the dynamic model of the internal combustion engine and the PMBL motor, is solved with using linear matrix inequality, which is the powerful method for such a system. The results shows that the proper Kalman Filter Gain may cause the best fault detection, otherwise the detection method may be unavailable.

APPENDIX

$$A(\omega_0)=\begin{bmatrix} 0 & \omega_0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\omega_0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -k/J_{ICE} & 0 & -C/J_{ICE} & \omega_0 & -k/nJ_{ICE} & 0 & -C/J_{ICE} & 0 & 0 & 0 \\ 0 & -k/J_{ICE} & -\omega_0 & -C/J_{ICE} & 0 & k/nJ_{ICE} & 0 & C/J_{ICE} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & \omega_0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\omega_0 & 0 & 0 & 1 & 0 & 0 \\ k/nJ_M & 0 & C/nJ_M & 0 & -k/4J_M & 0 & -C/4J_M & \omega_0 & 3p\lambda/2J_M & 0 \\ 0 & k/nJ_M & 0 & C/nJ_M & 0 & -k/4J_M & -\omega_0 & -C/4J_M & 0 & 3p\lambda/2J_M \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/\tau_e & \omega_0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_0 & -1/\tau_e \end{bmatrix}$$

$$B_1 = B_4 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1/\tau_e & 0 \\ 0 & -1/\tau_e \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/J_{ICE} & 0 \\ 0 & 1/J_{ICE} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad B_1 = 0,\; C = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}^T, \quad D_4 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix}, \quad D_1 = D_2 = D_3 = 0,\; X' = \begin{bmatrix} \bar{\theta}'_{ICE,R} \\ \bar{\theta}'_{ICE,I} \\ \bar{\omega}'_{ICE,R} \\ \bar{\omega}'_{ICE,I} \\ \bar{\theta}'_{el,R} \\ \bar{\theta}'_{el,I} \\ \bar{\omega}'_{el,R} \\ \bar{\omega}'_{el,I} \\ \bar{I}'_{q,R} \\ \bar{I}'_{q,I} \end{bmatrix}$$

NOMENCLATURES

θ_{ICE} : Shaft Position of Internal Combustion Engine (ICE)
ω_{ICE} : Angular Speed of ICE
J_{ICE} : Inertia mass moment of Flywheel
T_D : Torque Generated by ICE
T_l : Exogenous load torque
K: Stiffness of the belt for coupling system
C: Damping Coefficient of the belt for coupling system
N: Ratio of Torque coupler belt between electric motor and ICE
θ_{el} : Rotor Position
ω_{el} : Rotor angular speed
L: Length of the connecting rod
R: Radios of the crankshaft
m_a: Connecting rod mass
m_p: Piston mass
i_d: d component of armature current
i_q: q component of armature current
v_d: d component of stator voltage
v_q: q component of stator voltage
P: Number of pole pairs
R: Stator resistance per phase
L_d: d component of stator inductance
L_q: q component of stator inductance
λ : Flux linkage per phase
J_M: Inertia mass moment of electric motor

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BIOGRAPHIES

Davood Habibinia was born in Urmia, Iran in 1982. He received the B.Sc. degree in Control Engineering from University of Shiraz, Shiraz, Iran in 2003 and the M.Sc. degree in Electric Machinery and Drive from Iran University of Science and Technology, Tehran, Iran in 2006. He is now studying the Ph.D. degree in Electrical Engineering (Electric Machinery and Drive) at University of Tabriz, Tabriz, Iran since 2012. His research interests are in the area of electrical machines and transformer design, power electronic converters design, HVDC systems design and control, distributed generation and renewable energy conversion systems. He is now an academic member of Electrical Engineering Group at Urmia University of Technology, Urmia, Iran.

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