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Application of Fuzzy Logic Controller for Development of Control Strategy in PHEV

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Abstract: In this paper, implantation of fuzzy logic controller for parallel hybrid electric vehicles (PHEV) is presented. In PHEV the required torque is generated by a combination of internal-combustion engine (ICE) and an electric motor. The controller simulated using the SIMULINK/MATLAB package. The controller is designed based on the desired speed for driving and the state of speed error. In the other hand, performance of PHEV and ICE under different road cycle is given. The hardware setup is done for electric propulsion system; the system contains the induction motor, the three phase IGBT inverter with control circuit using microcontroller. The closed loop control system used a DC permanent generator whose output voltage is related to motor speed. Comparison between simulation and experimental results show accurate matching.

Key words: Hybrid electric vehicles-induction motor, internal combustion engine, fuzzy logic control.

List of Symbols

A_0, ……, A_8	Constant equation factors
B	Viscous constant
F_{out}	Output pf fuzzy controller
$g(P_{m\cdot})$	Function introduced in Eq. (11)
N_{er}	Error of speed
i_{ds} & i_{dr}	Direct stator and rotor phase current
i_{qs}	Quadrature stator phase current
i_{qr}	Quadrature rotor phase current
i_r	Rotor current
i_s	Stator current
J	Friction constant
L_s	Stator per phase leakage inductance
L_r	Rotor per phase leakage inductance
M	Mutual magnetizing inductance
n	Motor speed (r.p.m)
N_{mes}	Error of speed measurement,
P_{amb}	Ambient pressure
P_m	Motor power (watts)
r_s & r_r	Stator and rotor/phase resistance windings
T_e	Developed torque
T_l	Load torque
T_{eng}	ICE torque
T_{Load}	Load torque
V_{ds}	Stator direct axises voltage
V_{qs}	Stator quadrature axises voltage
V_s & V_r	Stator and Rotor voltage
x_1	Speed of engine
x_2	Manifold pressure
θ	Throttle angle
λ_s & λ_r	Flux linkage for stator & rotor
ω_r	Rotor angular velocity

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1. Introduction

The early air quality concerns in 1960s and energy crisis in 1970s have brought EV’s back again, besides air pollution, and ICE vehicles and their extremely low efficiency. Hence, the problem associated with ICE vehicles is environmental, economical as well as political. These concerns have forced governments all over the world to consider alternative vehicle concepts [1]. Nevertheless, regulations become ever stricter, until the State of California passed a law in 1990 requiring that EV account for certain percentage of vehicles sales, beginning with the 1998 model year. Considering that oil is a finite resource and will some-day disappear, finding sustainable alternative energy is perhaps the most important issue facing us in the long run. Hoping that 21st century the environmental century.

Nowadays there more than 600 million vehicle on the street and roads of the world. Of these, more than 100000 are EV [2]. EV's and hybrid-electric vehicles (HEV's) over the most promising solution to reduce vehicular emission. The short range associated with EV's still remains limitations of this technology.

HEVs produce the power required to drive the vehicle by a combination of two sources, an ICE and an electric motor. HEVs seem to be viable alternative to the ICE at the present. They can be generally classified as series or PHEV. In series HEVs, same as EVs, all the torque required to drive the vehicle is provided by an electric motor. On the other hand, in PHEVs, the torque obtained from the ICE is mechanically coupled to the torque produced by an electric motor [3]. In PHEVs, operation of each sources (ICE or electric motor), and amount of their contribution in production of torque at any time, will be decided by a controller. The choice of an electrical motor is important for better HEV design, so comparisons were done for different motor types and at different power rating [4-6]. Due to its availability, low cost, good performance and simple control, IM is chosen in this work.

2. System Model Descriptions

In this section, the model of PHEV power train parts is presented. The main parts of the system are shown in Fig. 1.

2.1 Induction Motor (IM)

The stator and rotor equations that represent the IM are given in Refs. [7-8]: Applying Park's transformation IM equations in D-Q reference frame are

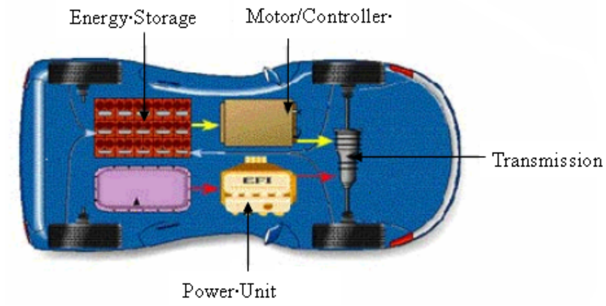


Fig. 1 Main parts of PHEV.

$$V_{Sph} = r_s i_{Sph} + \frac{d\lambda_{sph}}{dt} \quad (1)$$

$$V_{Rph} = r_r i_{rph} + \frac{d\lambda_{rph}}{dt} \quad (2)$$

$$V_{ds} = r_s i_{ds} + L_s \frac{di_{ds}}{dt} - M \frac{di_{dr}}{dt} \quad (3)$$

$$V_{qs} = r_s i_{qs} + L_s \frac{di_{qs}}{dt} - M \frac{di_{qr}}{dt} \quad (4)$$

$$0 = M \frac{di_{ds}}{dt} - M\omega_r i_{qs} - r_r i_{dr} - L_r \frac{di_{dr}}{dt} + L_r \omega_r i_{qr} \quad (5)$$

$$0 = M \frac{di_{qs}}{dt} + M\omega_r i_{ds} - r_r i_{qr} - L_r \frac{di_{qr}}{dt} - L_r \omega_r i_{dr} \quad (6)$$

and the mechanical equations are

$$T_e = M[i_{qs}\, i_{dr} - i_{qr}\, i_{ds}] \quad (7)$$

$$T_e = T_l + J \frac{d\omega_r}{dt} + B\omega_r \quad (8)$$

The above motor equations are simulated using MATLAB/ SIMULINK software package [9].

2.2 Engine Dynamic Model

A simple model of engine introduced in Ref. [10] is used. This model includes a two-state dynamic model, whose output is the ICE torque. The states of the model are the speed of engine (x_1) and the manifold pressure (x_2).

$$\dot{x}_1 = -280.92 - \frac{3337.3}{x_1} + 818.77x_2 - 307.29x_2^2 + 0.91185 * x_1 * x_2 + 0.24428x_1 - 0.000764x_1^2 - 7.1429T_{load} \quad (9)$$

$$\dot{x}_2 = 0.15126 - 0.0371 * x_1 * x_2 + 0.01393 * x_1 * x_2^2 - 0.00004133 * x_1^2 * x_2 + 0.41328 * g(x_2) * u \quad (10)$$

$$T_{eng} = -39.32 - \frac{467.22}{x_1} + 114.62x_2 - 43.02 * x_2^2 + 0.1276 * x_1 * x_2 + 0.03419 * x_1 - 0.000107 * x_1^2 \quad (11)$$

$$g(P_m) = \begin{cases} 1 & P_m \le \frac{P_{amb}}{2} \\ \frac{2}{P_{amb}} \sqrt{P_{amb} P_m - P_m^2} & P_m > \frac{P_{amb}}{2} \end{cases} \quad (12)$$

$$f(\theta) = 2.821 - 0.05231\theta + 0.10299\theta^2 - 0.00063\theta^3 \quad (13)$$

where T_{eng} is the ICE torque, T_{Load} is the load torque, θ is the throttle angle, P_{amb} is the ambient pressure, and g is a function introduced in Eq. (11).

3. Speed Control of IM Using FLC

The two main types of speed control of IM are the scalar control and the vector control. Sinusoidal PWM (SPWM) used in this work. Utilizing the FLC and it has three main components [11-14]. The membership functions of FLC to control speed of an IM contain two inputs which are the speed error ($\Delta\omega$) and the change in error ($\Delta\omega$*) and one output (ω_c) [15-17].

In this study, performance of IM drive system with FLC controller is given. The proposed method to deal with FLC is to start at the moment of making FLC as software program, the different components of FLC (membership functions, rules) takes a large size in the software program which complicate the controlling process. The idea is simply to model FLC as an equation between error speed and output control of FLC it is called arithmetic FLC (AFLC) [18-19]. Simulation block diagram of the IM drive system using FLC are shown in Fig. 2.

4. PHEV

PHEV system contains two main components, which are the IM and the ICE. A complete drive cycle (C-cycle), contains rise, fall, constant and stop driving profile with a total time of 55 seconds as shown in Fig. 3. In this drive cycle IM drive the vehicle alone in some intervals of it while in others to speed up the vehicle uses both the IM and the ICE. In some intervals of the driving cycles in non-urban areas PHEV is driven by ICE only. Therefore, the vehicle is simulated when driven by both IM and ICE. The results show that the vehicle speed using the ICE is higher than the case of the vehicle is driven by the electric motor only.

When using the electric motor only the transient performance of the vehicle speed to reach steady state is better. In some intervals of the driving cycles, the vehicle speed is higher than the maximum speed obtained when the vehicle driven by ICE. So, the electric motor is used to meet the required driving cycle.

The simulation results in this case for the three speeds (vehicle, electric motor, and ICE speeds) are shown in Fig. 4. In some other cases the vehicle is driven by the IM and the vehicle speed required increased according to the divining C cycle. So, the ICE is shared the IM to drive the PHEV.

Also, the fuel consumption and exhaust of CO, NOx results are shown in Fig. 5 which shows remarkable improvement.

5. System Experimental Setup

The experimental drive system of IM using AFLC, contains the power circuit, drive circuit and control as shown in Fig. 6. The different part of experimental set up as IM with mechanical load and DC generator are shown in Fig. 7. The flowchart of the algorithm for

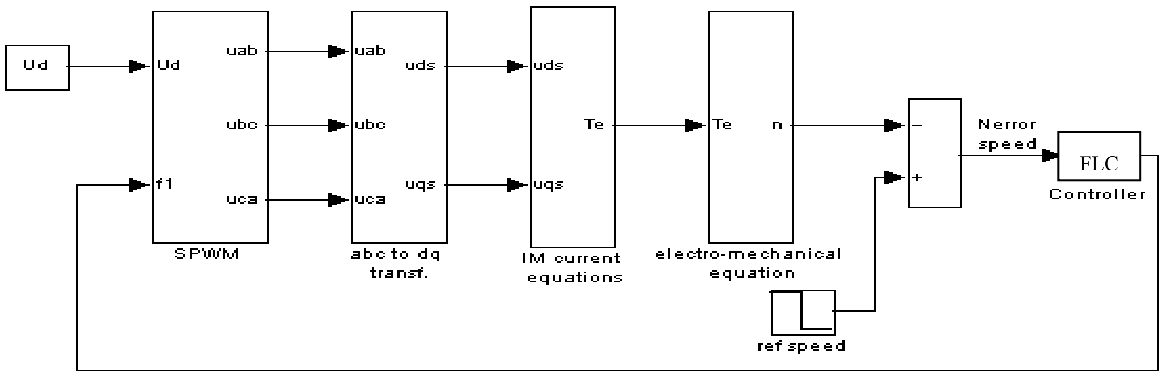


Fig. 2 Simulation block diagram of the IM drive system using FLC.

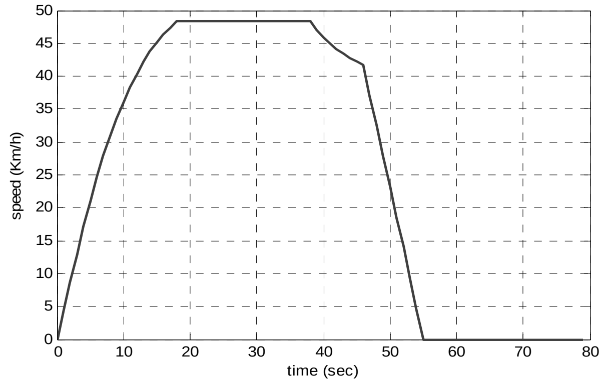


Fig. 3 C-driving cycle.

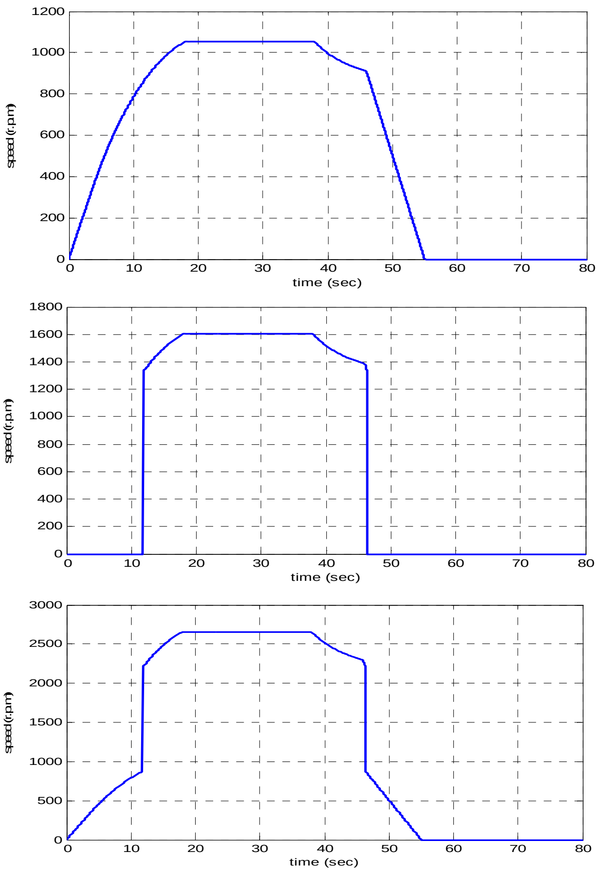


Fig. 4 Various speeds of HEV with C-cycle.

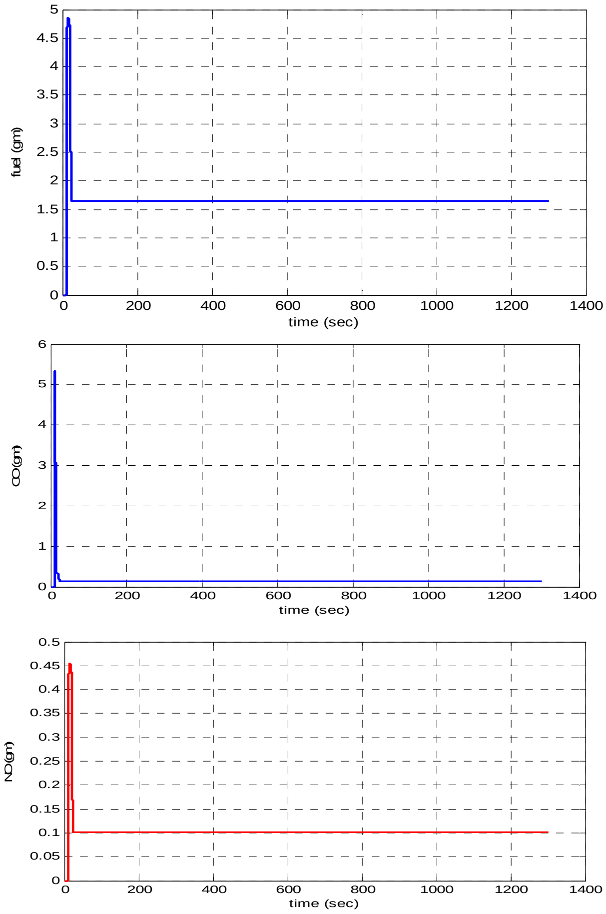


Fig. 5 Fuel consumption and CO, NOx pollution results.

control program used in this work is shown in Fig. 8. The input data are reference speed and measurement speed, while the output is PWM signal to drive circuit. In this program, we calculate the voltage and frequency of IM depend on the speed reference.

The output SPWM control signals of two IGBT switches in the same leg (connected with the same phase). Changing the reference speed signal changes will change the frequency of the SPWM signal. The

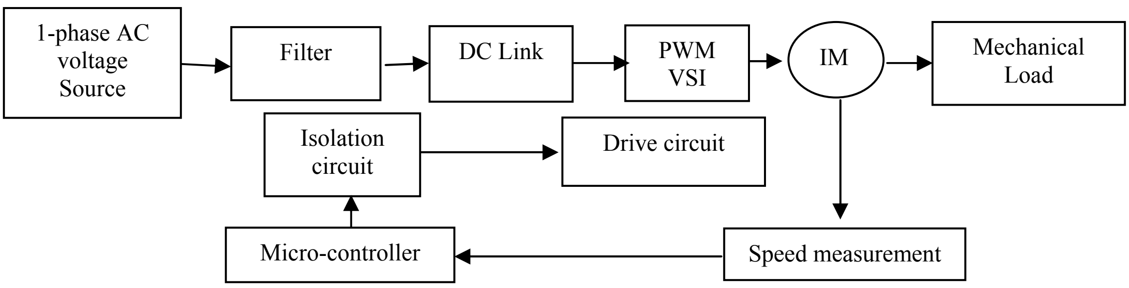


Fig. 6 Block diagram of experimental system.

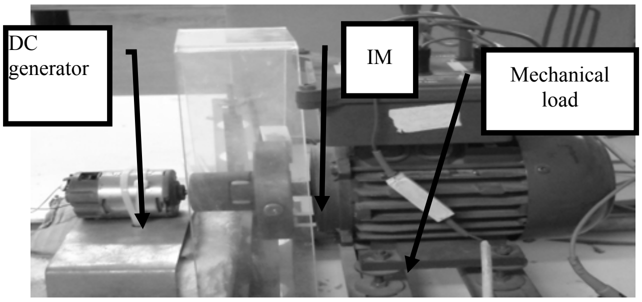


Fig. 7 A photo of experimental system set up.

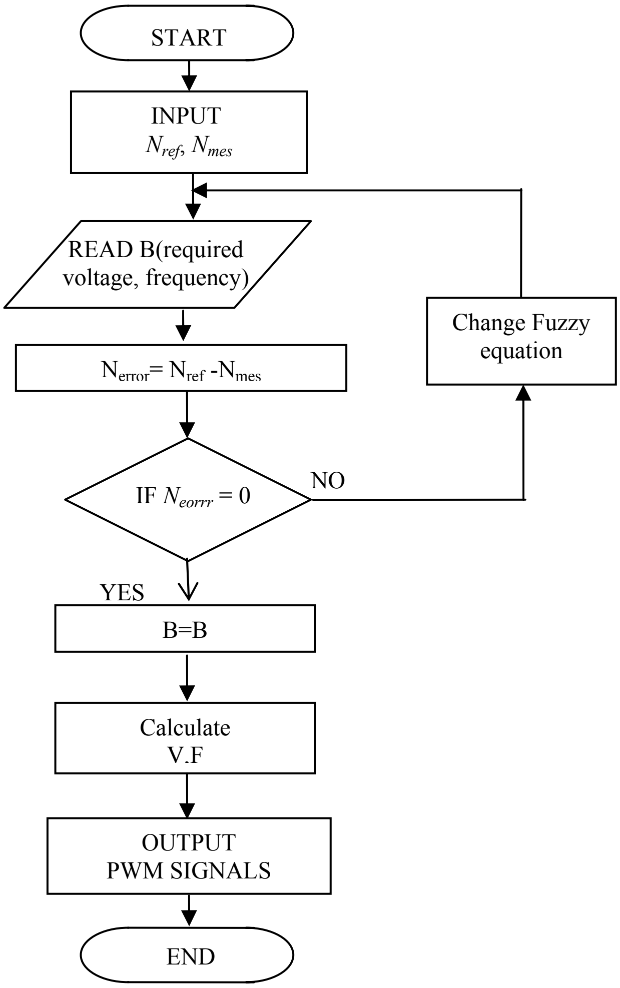


Fig. 8 Flow chart of control program.

filter capacitor current and it is clear that the capacitor current contains spikes due to the charging and the discharging at high switching frequency. While the inductor current is shown in Fig. 9, Fig. 10 shows performance when changing speed of IM, from 800r.p.m to 300r.p.m and as shown the trace of the actual speed to reach steady state value behind the reference speed by very small time. In the mean time,

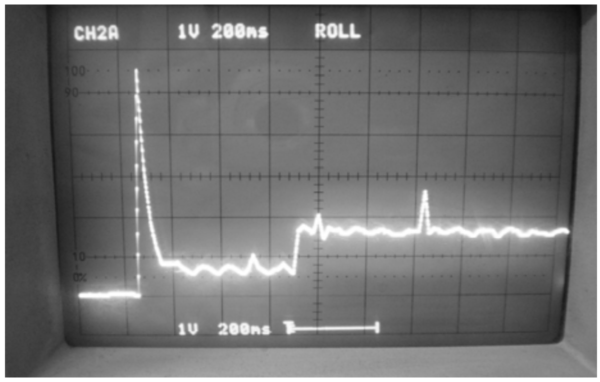
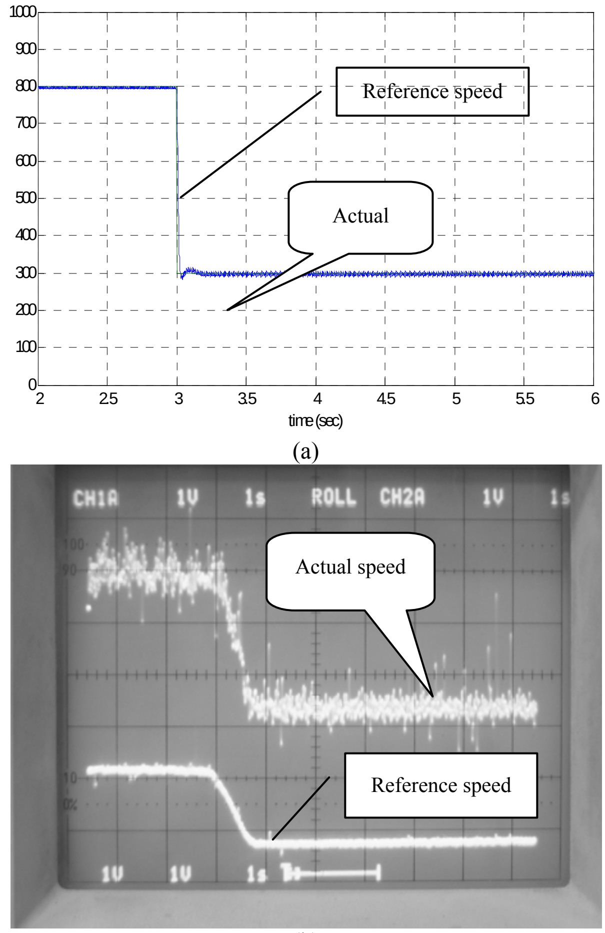


Fig. 9 Inductor current (transient state).



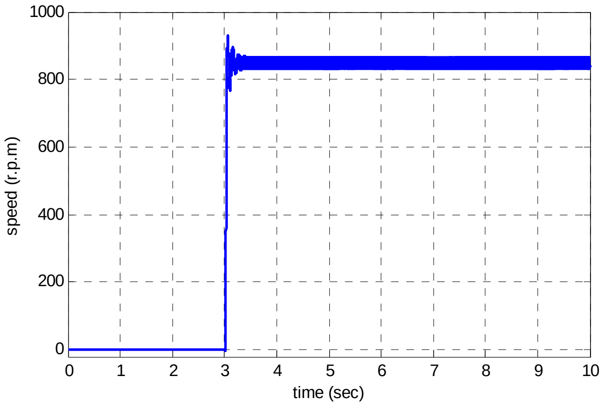
(b)

Fig. 10 Comparison of simulation result (a) and experimental result (b) (800r.p.m to 300r.p.m).

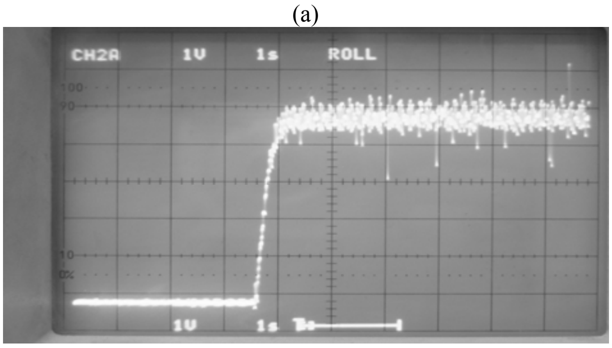
the comparison done at starting speed as shown in Fig. 11. While, the line motor voltage harmonic spectrum is shown in Fig. 12.

6. Conclusions

In this work, AFLC applied to control PHEV. AFLC



(a)



(b)

Fig. 11 Comparison of simulation result (a) and experimental result (b).

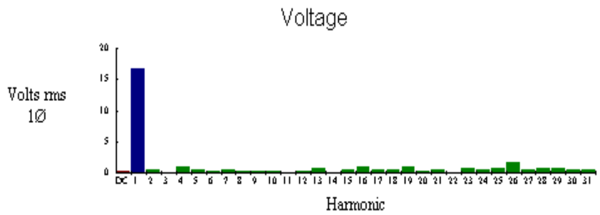


Fig. 12 Motor line voltage harmonics spectrum.

reduces largely size of the software program, and easier in simulation using SIMULINK/MATLAB software package. The controller was designed based on the desired speed for driving and the state of change of speed. AFLC used to obtain the desired speed then micro-control takes very short time to reach the actual value. Analysis of IM with FL at variable load torque and speed is given. Simulation of PHEV under different driving cycles appears that starting of the vehicle in all the driving cycles by the electric motor since it has better starting performance than ICE. The system performance is stable and has good dynamic response under different disturbance.

Using PHEV under different road cycles shows that the ICE is used for long operating periods in non-urban areas, but the IM is used for long operating periods in urban areas to minimize air pollutions and to achieve healthy environment. The experimental results show that the IM drive system using AFLC controller has a good dynamic response. Simulation and experimental results are much similar.

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APPENDIX

(1) IM parameters are:

P_{rated} = 37 kW	V_L = 460 V
f = 50Hz	$2p$ = 4
n_{rated} =1780 r.p.m	r_s = 0.087 Ω
r_r = 0.228 Ω	L_s = 0.00008 H
L_r = 0.00008 H	M = 0.0347 H
J = 1.662 Kg. m2	B = 0.12 N.m.s

(2) IM used in the experimental work are:

P_{rated} = 0.25 kW	V_{LL} = 380V
f = 50Hz	$2p$ = 2
n_{rated} = 2700 r.p.m	T_{rated} = 0.884 N.m
r_s = 35 Ω	r_r = 20 Ω
L_s = 0.12 H	L_r = 0.12 H
M = 1.5 H	J = 0.00024 Kg. m^2
B = 1.85e-04 N.m.s	

(3) ICE parameters

Pe (max) = 40 kW	Fuel = 20 liters
Ne = 9000 r.p.m	gr_2 = 3.6