Using Fuzzy Logic Self-Tuning PI Gain Controller Z-Source Inverter in Hybrid Electric Vehicles

An Wen Shen, Cong-Thanh Pham, Phan Quoc Dzung, Nguyen Bao Anh, and Le Hoang Viet

Abstract—**This paper presents a new algorithm to control the peak dc-link voltage (PDV) across the inverter bridge in Z-Source inverters (ZSI) by applying self-tuning fuzzy PI controller (SFP) with robust structure and non-linear characteristic. In particular, this so-called SFP based control algorithm is applied to closed loop speed control system of induction motor, which relies on direct torque control combined with modified space vector modulation (DTC-MSVM) control strategy. More importantly, the combination of SFP based control algorithm and DTC-MSVM with many exceptional features such as: fast torque response, low steady state torque ripple, and high accurate is the best candidate for controlling the PDV in hybrid electric vehicles (HEV) applications. In this way, the PDV is more adaptive to the sudden change of dc input voltage (DIV). The transient response of PDV is thus improved with low disturbance for output voltage stabilization in the inverter bridge. As a result, we achieve higher robustness and performance of speed motor control system. Our new SFP based control algorithm is verified in both simulation and experimental implementation using MATLAB and dSPACE DS1103, respectively.**

Index Terms—**Buck-boost; PWM; DTC-SVM; voltage source inverters (VSIs), induction motor speed control; z-source inverter; hybrid electric vehicles.**

I. Introduction

In a conventional voltage source inverter, the two switches of any phase leg cannot be gated at the same time because this may cause a short circuit situation and thus destroy the inverter. In addition, the maximum output voltage cannot exceed the dc bus voltage. These limitations in such conventional voltage source inverter can be overcome by using ZSI [1]. Actually, the ZSI is a power electronic converter with many advantages such as buck-boost characteristics, lower cost, and especially higher efficiency compared to traditional dc-dc converter [2], [3]. As a more sophisticated design of ZSI, high-performance ZSI (HP-ZSI) copes with dc-link voltage drops for wide range of load with even using small inductor while guaranteeing a simple design. Thus, HP-ZSI is more suitable for HEV applications [4], [5].

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In control systems of the HEV, the control requirements are very high and stringent; they are fast torque response, low steady state torque ripple, high accuracy, wide speed range, and high torque at low speed. It is really challenging to meet all of these requirements by using traditional control methods of induction motor (IM) such as: voltage/hezt, field oriented control and traditional direct torque control, but DTC-SVM control method can succeed [6], [7].

In HP-ZSI, the dc link voltage is in square waveform, it is zero when the inverter bridge is in the shoot-through zero state, but is peak value when the inverter bridge is in the non-shoot-through state [1]. Consequently, the dc link voltage cannot be controlled directly. Alternatively, there have been many studies proposed to control the average value of dc link voltage by controlling the capacitor voltage. However, the capacitor voltage (V_c) is somewhat equivalent to the PDV of inverter, which the relationship between the PDV ($\hat{V}_i$) and the capacitor voltage are the non-linear. Additinally, when ZSI parameters (resistor of capacitor, capacitor, resistor of inductor, inductor, shoot through duty d_o) are variations, non-minimum phase phenomenon of ($\hat{V}_i/d_o$) transfer function is more serious than that of the control to (V_c/d_o) transfer function [8]. Therefor, controlling the value of dc link voltage by controlling the PDV is most suitable for ZSI.

In this paper, applying SFP to control the PDV is promise for non-minimum-phase or non-linear characteristic of ZSI. In particular, SFP means that the two parameters Kp, Ki of conventional PI controller are tuned by using fuzzy inference tuner to improve quality control of non-liner systems such as: without error steady state, less overshoot, decrease rise time and faster settling time. SFP of ZSI is set up to closed loop speed control system of induction motor, which relies on DTC-MSVM control strategy. More importantly, the combination of SFP and DTC-MSVM with many exceptional features such as: fast torque response, low steady state torque ripple, and high accurate is the best candidate for controlling the PDV in HEV applications. In this way, the PDV is more adaptive to the sudden change of DIV. The transient response of PDV is thus improved with low disturbance for output voltage stabilization in the inverter bridge. As a result, we achieve higher robustness and performance of speed motor control system. Our new SFP based control algorithm is verified in both simulation and experimental implementation using MATLAB and dSPACE DS1103, respectively.

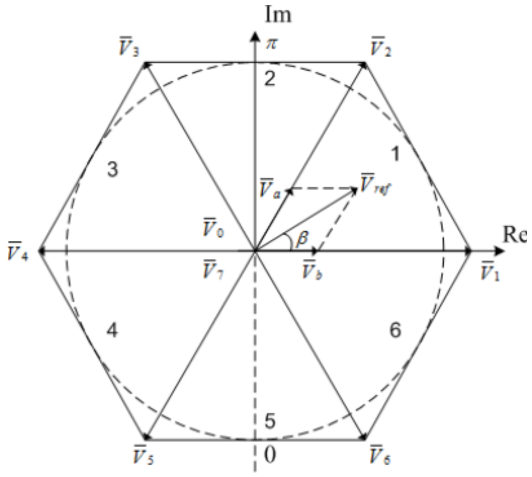


Fig. 1. Voltage vector through conventional SVM of VSI.

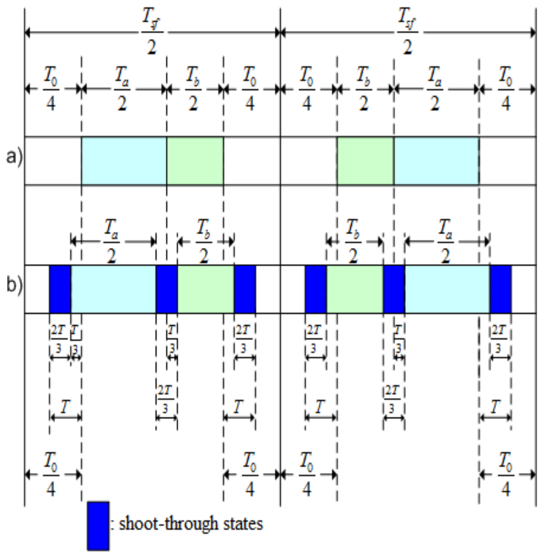


Fig. 2. Modified space vector PWM (MSVM).a)Switching

II. Analysis Control Methods

A. Dynamic Model of Induction Motor (IM), DTC-SVM

1) Nomenclature

Three-phase IM 1Hp model in stationary frame equation base on dynamic model (Kron Equation) [11] are given as:

$v_{dqs} = v_{ds}; v_{qs} =$ d-axis;q-axis stator voltages;

$i_{dqs} = i_{ds}; i_{qs} =$ d-axis ; q-axis stator currents;

$\varphi_{dqs} = \varphi_{ds}; \varphi_{qs} =$ d-axis; q-axis rotor flux linkages;

$T_e; T_l =$ The electromagnetic torque; load torque;

2) Dynamic model of IM

The corresponding stationary frame equations [11] can be derived easily as follows:

Stator Voltage:

$$v_{dqs} = R_s i_{dqs} + \frac{d\varphi_{dqs}}{dt} \tag{1}$$

Rotor Voltage:

$$0 = R_r i_{dqr} + \frac{d\varphi_{dqr}}{dt} \pm \omega_r \varphi_{dqr} \tag{2}$$

Stator Flux:

$$\varphi_{dqs} = L_{ls} i_{dqs} + L_m \left(i_{dqs} + i_{dqr} \right) \tag{3}$$

Rotor Flux:

$$\varphi_{dqr} = L_{ls} i_{dqr} + L_m \left(i_{dqs} + i_{dqr} \right) \tag{4}$$

Mechanical:

$$T_e = \frac{3}{2}\frac{p}{2}\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds} \right) \tag{5}$$

$$T_e - T_l = J_m \frac{2}{p}\frac{d\omega_r}{dt} + B_m \omega_r \tag{6}$$

B. Direct Torque Control-Modified Space vector Modulation (DTC-MSVM)

1) MSVM

The space vector pulse width modulation (SVM) method have widely used at regulated PWM inverter due to a higher modulation index and lower current harmonics in [12]. Base on principles of ZSI [13], the shoot-through states (STS) should be inserted period intervals of SVM are called the modified space vector modulation (MSVM) to boost-buck the dc-link voltage of the ZSI, to reduce the common (RCM) voltage, not require dead-time protection short circuit at two switches any of the same phase leg and to achieve alike optimal harmonic performance by given [1] and are expressed at Fig. 2 b).

where V_0, V_7 are two zero vectors and STS is the third zero vector in ZSI, where V_1 to V_6 are the six active vectors in Fig. 1. When V_{ref} rotate around section (1-6) of hexagon while (a, b) are changed: (a, b) = (1, 2); (2, 3); (3, 4); (4, 5); (5, 6) in every sector, respectively. In one sampling interval, Va and Vb are applied at times T_a and T_b, respectively, and the zero vector is applied at time $T_{sf} = (T_a+T_b)+T'_0+T_{sr}$ where $T'_0 = T_0 - T_{sr}$. Consequently, from (7), the reference voltage vector V_{ref} can be given by

$$\bar{V}_{ref} = \bar{V}_a T_a + \bar{V}_b T_b \tag{7}$$

$$T_a = \sqrt{3}.\frac{V_{ref}}{\hat{V}_i}.T_{sf}.\sin\left(\frac{\pi}{3} - \beta\right) \tag{8}$$

$$T_b = \sqrt{3}.\frac{V_{ref}}{\hat{V}_i}.T_{sf}.\sin(\beta) \tag{9}$$

where β is the angle between the reference voltage vector V_{ref} and voltage vector V_1, $\hat{V}_i$ is the PDV.

The MSVM Fig. 2b). where T_{sr} is shoot-through time. From Fig. 2. the STS are evenly assigned to each phase with $2T/3$ within zero voltage period $T_0/4$ and $T/3$ within active voltage period $T_a/2$ and $T/3$ within active voltage period $T_b/2$, where T_a and T_b are unchanged. So the STS does not affect the SVM control method of the inverter, and it is limited to the zero state time T_0. Where T are determined by (10).

$$T_{sr} = 6.2.\frac{T}{3} = 4.T \rightarrow T = \frac{T_{sr}}{4} \tag{10}$$

And from [14] we have

$$o < d_0 = \frac{T_{sr}}{T_{sf}} < \frac{1}{2} \rightarrow o < T_{sr} < \frac{T_{sf}}{2} \tag{11}$$

where d_o is shoot through duty. From (10) and (11) we have:

$$0 < T < \frac{T_{sf}}{8} \tag{12}$$

Therefore, controlling the dc-peak voltage across the inverter bridge have to found on limited of time T.

2) DTC-MSVM

The DTC-MSVM are combined from DTC and MSVM Fig. 2. The DTC-MSVM there are features the same with DTC-SVM such as: fast torque response, low steady-state torque ripple, low current distortion, high-performance dynamic characteristics and accuracy. Especially the aim of this method to control the PDV ($\hat{V}_i$) by regulate STS while DIV decrease or increase that is not affect speed control and torque motor [5], [7]. Therefore, the DTC-MSVM is the best candidate for HEV applications Fig. 3.

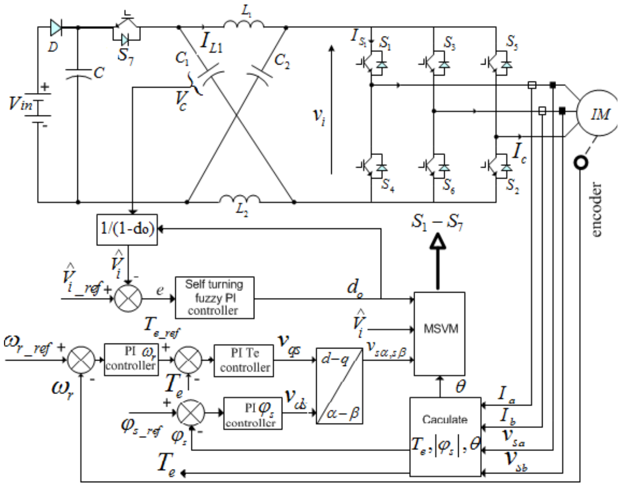


Fig. 3. DTC-MSVM block diagram.

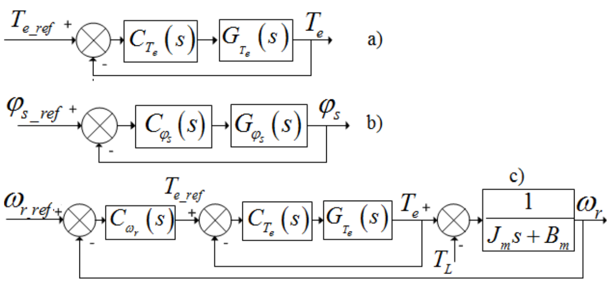


Fig. 4. Block diagram electromagnetic torque a) stator flux controller b) and speed controller controller c).

C. A new Algorithm Control the PDV across the Inverter Bridge Due to SFP, Stator flux Controller, Electromagnetic Torque Controller, Speed Controller

1) Electromagnetic torque controller

The electromagnetic torque open loop dynamics is presented by the writing of the closed loop transfer function is divided between the electromagnetic torque and the q-axis stator voltage [15]. The open loop transfer function $G_{Te}(s)$ in s-plane is expressed by:

$$G_{Te}(s) = \frac{T_e(s)}{V_{qs}(s)} = \frac{s + A_{Te}}{s^2 + B_{Te}s + C_{Te}} \tag{13}$$

where:

$$A_{Te} = \frac{K_t L_r}{\sigma};\ B_{Te} \frac{R_s L_r + R_r L_s}{\sigma};\ C_{\varphi} = \frac{3p^2 K_t L_r \left|\varphi_{s-ref}\right|^2}{2J_m \sigma}$$

$\sigma = L_r L_s - L_m^2$. All of these parameters are given in TABLE I. Electromagnetic torque controller parameters $C_{T_e}(s)$ are calculated in sisotool of Matlab, base on PI controller Fig. 4 a), Fig. 3.

2) Stator flux controller

Especially, the dynamic flux in open loop is presented by the writing of the closed loop transfer function between stator flux and d-axis stator voltage that based on the motor model (1) to (4) and from [15] the open-loop flux transfer function $G_{\varphi}(s)$ in s-plane is written by:

$$G_{\varphi}(s) = \frac{\varphi_{ds}(s)}{V_{ds}(s)} = \frac{s + A_{\varphi}}{s^2 + B_{\varphi}s + C_{\varphi}} \tag{14}$$

where: $A_{\varphi} = \frac{L_r L_s}{\sigma};\ B_{Te} = B_{\varphi};\ C_{\varphi} = \frac{R_r R_s}{\sigma}$. All of these parameters are also given in TABLE I. Flux controller parameters $C_{\varphi_s}(s)$ are also calculated in sisotool of Matlab, base on PI controller Fig. 4b), Fig. 3.

3) Speed controller

Because of the variation of the load torque, speed controller motor is designed based on Fig. 4c), [5] so that it obtain the required response during load changes is given by:

$$K_{p\omega_r} = 2J_m \xi \omega_n - B_m \tag{15}$$

$$K_{i\omega_r} = J_m \xi \omega_n^2 \left(2\xi^2 - 1\right) \tag{16}$$

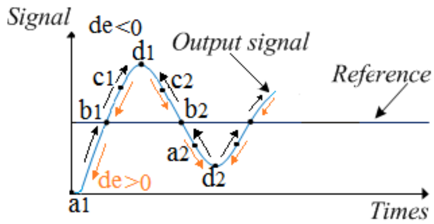
where: ω_n and ξ are the dynamics response and desired damping, respectively.

4) A new algorithm control the PDV across the inverter bridge due to SFP

The PID controller is the most popular controller and widely used to improve the performance of systems control in industry. Additionally, for some small inertia of systems, they are often used to the PI controller. In addition, the PI controller can be attributed partly easy to operate, functional simplicity and robust performance. However, in nonlinear control systems, the parameter variations or uncertain parameters, if using PI traditional controller the system response maybe very hard to get a good control performance because, while operating systems K_p, K_i gain of traditional PI controller don't tune itself due to parameter variations of the nonlinear plants [17].

a)

PID gain	Rise time	Over shot	Steady state error
K_p	↓↓	↑	↓
K_i	↓	↑	↓↓
K_d	—	↓↓	—



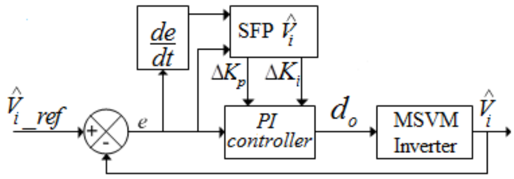


Fig. 5. Behavior of PID gain creasing [16] a) Rules SFP controller b) The PDV across the inverter bridge controller c).

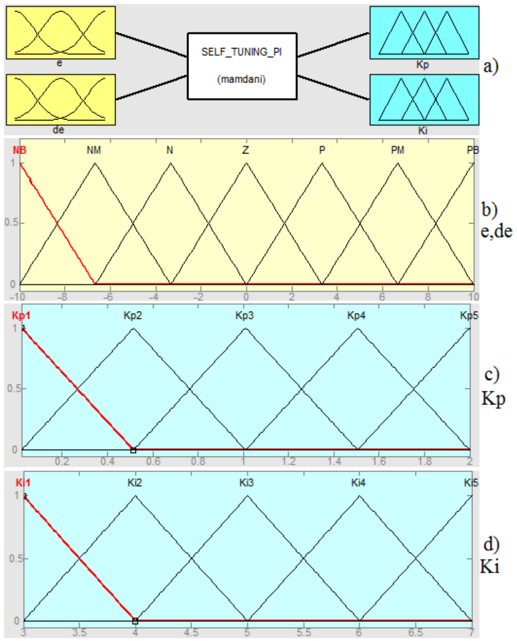


Fig. 6. Fuzzy inference with 2 input, 2 output a) Membership functions of input signal *e,de* b) Output signal K_p c),K_i d).

Therefore, this paper proposed control methods is SFP controller means that the two parameters K_p, K_i of conventional PI controller which gain of it are tuned by using fuzzy inference tuner (17) Fig. 5c) to improve quality control of systems such as: small error steady-state, less overshoot, decrease rise time and faster settling time. In addition, due to SFP has the advantage of adaptive, flexibility, high control precision, and robustness in speed control motor.

Following to the fuzzy structure, they include three blocks generally there are: fuzzification block, fuzzy inference engine that generates the fuzzy rules, adefuzzification block [9]. All of membership function are chosen triangle, the aggregation are used max-min and defuzzification method are used centroid method. In Fig. 6a) there are two input signal *e(t), de(t)* and two output signal K_p, K_i. Where *e(t)* is the error between reference signal and the output, *de(t)* is the derivation of *e(t)*

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{17}$$

where: u(t) is the signal control.

Base on the characteristics, specification of ZSI. Therefore, the linguistic variable levels of two input signal *e(t), de(t)* are assigned to seven levels, there are: NB: negative big; NM: negative middle; N: negative; Z: zero; P: positive; PM: positive middle; PB: positive big Fig. 6b). The linguistic variable levels of two output signal are assigned to five levels from small to large: K_{pj} and K_{ij} : $j=1 \rightarrow 5$ on Fig. 6c),d).

In Fig.5a) shown that K_p play critical role on rise time, K_i plays this critical role on error steady-state and K_d only effects on over shot [16], [18]. From Fig.5b) at around a1, the signal control should be tuned to increase dramatically in order to achieve fast rise time. So, K_p and K_i gain have to be tuned a big. Thus, the rule around a_1, are given:

If e is PB and de is Z, then K_p is K_{p5}, K_i is K_{i5} Fig.7a),b).At around b_1, the signal control should be tuned small so less overshoot and small error steady-state. So, K_p and K_i gain have to be tuned a small. Therefor, the following fuzzy rule is given:

If e is Z and de is NB, then K_p is K_{p1}, K_i is K_{i1} Fig.7a),b). Similar for around a_2, b_2, c_2, d_2 fuzzy rule are given in Fig.7a),b). In Fig.5c) transfer function $G_{\hat{V}_{i-do}}$ in s-plane was given by [5].

$$G_{\hat{V}_{i-do}}(s) = \frac{\hat{V}_{i(s)}}{D_o(s)} \tag{18}$$

where $\hat{V}_{i(s)}, D_o(s)$ are the PDV and shoot through duty in s-plane, respectively.

III. Simulation and Experimental Results

A. Simulation Results

a)

e \ de	NB	NM	N	Z	P	PM	PB
NB	Kp5	Kp5	Kp5	Kp5	Kp5	Kp5	Kp5
NM	Kp4	Kp4	Kp4	Kp4	Kp4	Kp4	Kp4
N	Kp3	Kp3	Kp3	Kp3	Kp3	Kp3	Kp3
Z	Kp1	Kp1	Kp1	Kp1	Kp1	Kp1	Kp1
P	Kp3	Kp3	Kp3	Kp3	Kp3	Kp3	Kp3
PM	Kp4	Kp4	Kp4	Kp4	Kp4	Kp4	Kp4
PB	Kp5	Kp5	Kp5	Kp5	Kp5	Kp5	Kp5

b)

e \ de	NB	NM	N	Z	P	PM	PB
NB	Ki5	Ki5	Ki5	Ki5	Ki5	Ki5	Ki5
NM	Ki3	Ki4	Ki4	Ki5	Ki4	Ki4	Ki3
N	Ki2	Ki3	Ki4	Ki5	Ki4	Ki3	Ki2
Z	Ki1	Ki2	Ki3	Ki4	Ki3	Ki2	Ki1
P	Ki2	Ki3	Ki4	Ki5	Ki4	Ki3	Ki2
PM	Ki3	Ki4	Ki4	Ki5	Ki4	Ki4	Ki3
PB	Ki5	Ki5	Ki5	Ki5	Ki5	Ki5	Ki5

Fig. 7. Rules of K_p a) And K_i b).

In order to verify the validity of the above analysis, using Matlab simulates a new algorithm control for DTC-MSVM control strategy for IM 5Hp in Fig.8d). In Fig.8d) shows response of DIV, time from 0 to 1s value of DIV is 500V, at time from 1s to 2s DIV decrease 10% (450V) after that at time from 2s to 3s DIV continue to decrease 10% (400V). The PDV and the dc-link voltage v_i decrease a little then immediately return to the steady-state (560V) is shown in Fig. 8a) and c). Especially, In Fig. 8c) show that PDV is controlled by using two algorithms, there are: self-tuning fuzzy PI and PI controller. These results was shown SFP controller tracking a reference signal ($\hat{V}_{i-ref}$ =560V) better than PI controller. These control methods also have the settling, overshoot and rise time less than PI controller when DIV is changed suddenly. Additionally, in Fig. 8b) duty d_o is also increase to the DIV sudden decrease at 1s, 2s. These simulation results are very appropriate with boost characteristics of ZSI.

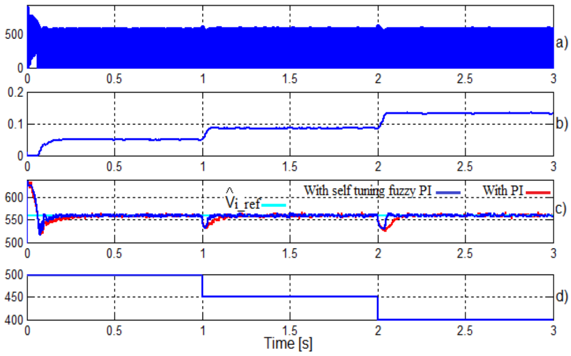


Fig. 8. The dc-link voltage v_i a) Duty d_o b) The PDV c) And DIV V_{in} d).

In Fig. 9a) when the DIV sudden decrease then the current waveform is unvaried. In addition, Fig. 9d) is shown low steady state electromagnetic torque T_e ripple and T_e is always tracking to load torque T_L when load torque sudden change. In Fig. 9b)*THD%* is shown current's low total harmonic distortion *THD% =3.58%*, speed motor is good steady-state show in Fig. 9c). Therefor, the PDV is controlled by SFP controller adapt to the DIV change, improves the transient response of PDV, increase robustness, applying good for speed control induction motor in the DTC-MSVM control strategy.

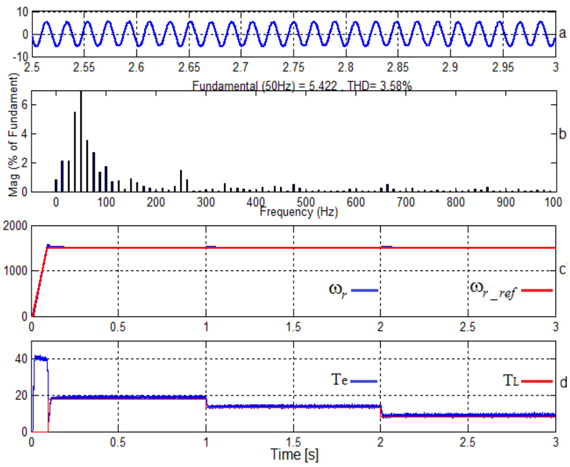


Fig. 9. The current a) THD% b) Speed motor c) Torque d).

B. Experimental Results

In Fig. 11 is figure experiments of the speed control IM 1Hp base on the DTC-MSVM control strategy and applying a new control method for PDV are proposed. Application DSpace DS1103 communicate with Matlab2008, using controlDesk.V4.1 to display experiment results in Fig. 10 that they are shown to DIV sudden decrease at 1s, 2s Fig. 10b). So, the duty do increase Fig. 10a), speed motor is also tracking to ωr_ref very good when DIV Vin sudden change, given by in Fig. 10c). Line current is given by Fig. 10d). So, experiment results are given in Fig. 10 very appropriate simulation results in Fig. 8 and Fig. 9.

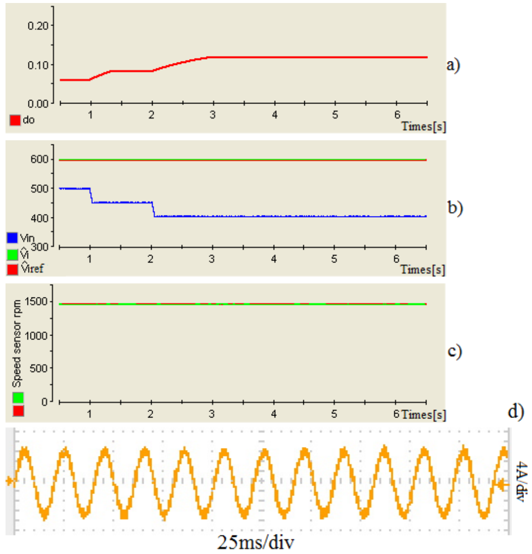


Fig.10. Duty d_o a) The peak dc-link voltage $\hat{V}_i$, the dc input voltage V_{in} b) And speed motor c) Line current d).

From simulation and experiment results show that characteristics of DTC-MSVM control strategy there are: when DIV decrease but PDV still hold voltage stabilization at 560V, so output voltage still stabilization. Additionally, DTC-MSVM control strategy is also to reduce the common voltage, not require dead-time protection short circuit at two switches any of the same phase leg increase robustness which it is the most focus to compare traditional DTC-SVM. Therefore, these characteristics are the most important reasons to choose DTC-MSVM control strategy for HEV applications.

TABLE I: PARAMETERS USED FOR SIMULATION AND EXPERIMENT OF DTC-MSVM

Parameter	Simulation	experiment
Z-source inductance (L_1 and L_2)(mH)	0.4	1.4
Z-source capacitance (C_1 and C_2)(mF)	0.5	0.25
Nominal power(P_n)W, voltage(V_n)(V)	3760;400	736;380
Frequency(f_n)(Hz)	50	50
Stator(R_s); rotor(R_r)resistance(Ω)	1.115;1.083	14.2;10
Stator(L_s); rotor(L_r)inductance (H)	0.006;0.006	0.03;0.03
Magnetizing inductance(L_m)(H)	0.2037	0.44
Switching frequency (f_{sf})(kHz)	10	2
Pole pairs(p)	2	2
Inertia(J_m)($kg.m^2$)	2*10⁻2	5.5*10⁻3
Friction factor(B_m)(N.m.s)	5.752*10⁻3	1.5*10⁻3
DC-link peak voltage ($\hat{V}_{i-ref}$) (V)	560	560
DC input voltage(V_{in})(V)	500,450,400	500,450,400
Speed motor (ω_{r-ref})(rpm)	1500	1490
load torque(T_L)(N.m)	18,13,8	3,2,1

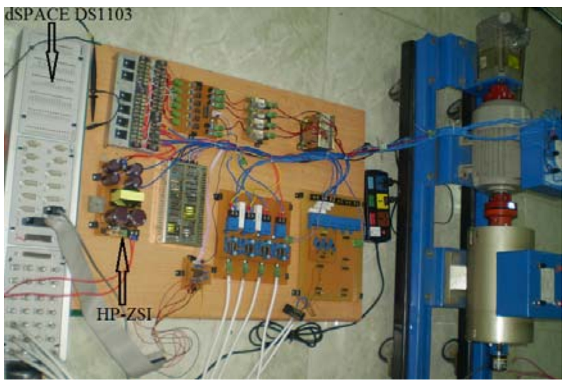


Fig. 11. The figure experiments.

IV. CONCLUSION

With simulation and experimental results are given to verify the proposed a new algorithm to control the PDV in ZSI due to SFP controller by using fuzzy logic which it adapt to DIV sudden change, in order to improves transient response of PDV, to solve the problems of the output voltage stabilization in the inverter bridge. More importantly, this new algorithm is applied in closed loop speed control system of induction motor base on the DTC-MSVM control strategy with many exceptional features such as: fast torque response, low steady state torque ripple, increase accurate of speed motor, to increases robustness of speed motor control, enhances disturbance rejection and increase performance of the system. Therefor, the combination of SFP based control algorithm and DTC-MSVM control strategy is the best candidate for HEV applications.

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