

## Self-Tuning Fuzzy PI-Type Controller in Z-Source Inverter for Hybrid Electric Vehicles

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### Article Info

#### Article history:

Received Jun 17, 2012

Revised Oct 10, 2012

Accepted Oct 19, 2012

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#### Keyword:

Buck-boost converter;  
PWM;  
DTC-SVM;  
voltage source inverters (VSIs),  
Induction motor speed control;  
Z-source inverter;  
Hybrid electric vehicles

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### ABSTRACT

This paper presents new algorithms to control speed Induction motor (SIM) and 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 (SFPA) is applied to a closed loop speed control system of induction motor, which relies on direct torque control scheme combined with modified space vector modulation (DTC-MSVM) control strategy with so many exceptional features (e.g. fast torque response, low steady state torque ripple, and high accurate). Additionally, SFPA is used to control SIM and PDV are more adaptive to the sudden change of parameters such as load torque, stator resistance and dc input voltage (DIV), respectively. The transient response of SIM and PDV are thus improved with less overshoot, short rise time, small steady-state error and fast settling time, with low disturbance for output voltage stabilization in the inverter bridge. As a result, we achieve higher accuracy and robustness of SIM control system. Our new SFPA is verified in both simulation and experimental implementation using MATLAB and dSPACE DS1103, respectively.

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## 1. INTRODUCTION

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 [1], [2]. In addition, ZSI can be overcome drawbacks in conventional voltage source inverter (VSI) such as the maximum output voltage can exceed the dc bus voltage, the two switches of any phase leg can be gated at the same time which it does not affect to short circuit situation and destroy the inverter [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].

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/hertz, field oriented control and traditional direct torque control, but DTC-SVM control method can succeed [6], [7].

The dc link voltage of HP-ZSI is in square wave form, the relationship between the PDV ( $V_i$ ) and the capacitor voltage are the non-linear [3], [8]. Therefore, the dc link voltage cannot be controlled directly which it is controlled by controlling PDV.

The design of the good controller greatly affects the performance of an electric drive system [9]. For some small inertia of systems, the PI controller is the most popular controller and widely used in industry with characteristics such as 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 [10]. These drawbacks of the traditional PI controller have inspired to the substitution of the traditional PI controller with adaptive control techniques, such as (e.g. sliding mode control, fuzzy logic controller, model reference adaptive control, SFP).

This paper proposed control methods due to SFPA to control SIM and PDV which it is more adaptive to the sudden change of parameters such as load torque, stator resistance and dc input voltage (DIV), respectively. These adaptation means that the two parameters  $K_p$ ,  $K_i$  of conventional PI controller are tuned by using fuzzy inference tuner while these change of parameters. Thus, the response of SIM and PDV are improved such as decrease error steady state, less overshoot, decrease rise time and faster settling time. In addition, the way SFPA has the advantages of adaptive, high performance, and increase robustness in PDV and SIM control strategies.

**2. ANALYSIS CONTROL METHODS**

**2.1. Dynamic model of IM**

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

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

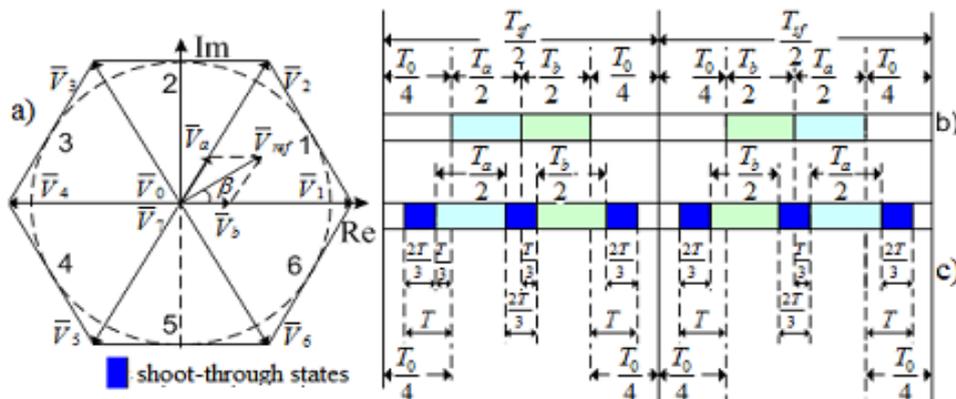


Figure 1. Traditional SVM of VSI a) Switching patterns for traditional SVM, b) Switching patterns for MSVM c).

Rotor Voltage:

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

Stator Flux:

$$\psi_{dqs} = L_{is} i_{dqs} + L_m (i_{dqs} + i_{dqr}) \tag{3}$$

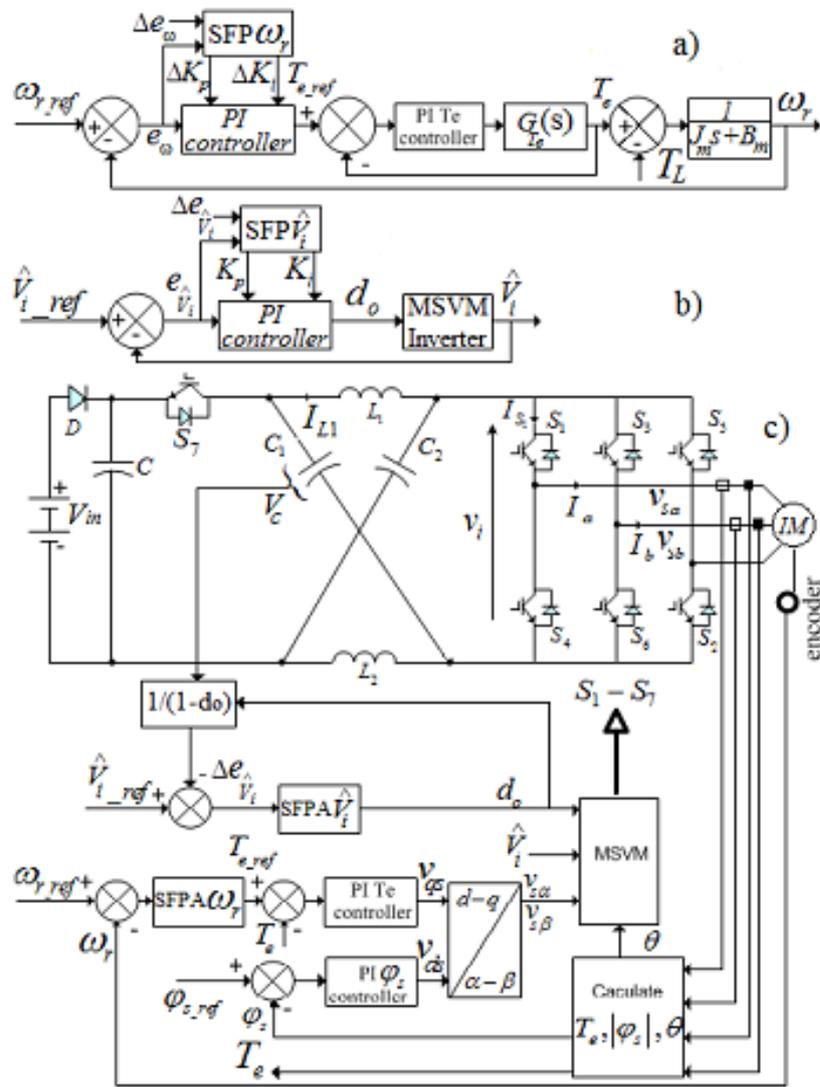


Figure 2. SIM controller a)  $V_i$  controller b) General DTC-MSVM block diagram c).

Rotor Flux:

$$\psi_{dqr} = L_{lr} i_{dqr} + L_m (i_{dqs} + i_{dqr}) \tag{4}$$

Mechanical:

$$T_e = \frac{3}{2} \left( \frac{P}{2} \right) (\psi_{dq} i_{qs} - \psi_{qs} i_{ds}) \tag{5}$$

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



$$T_b = \sqrt{3} \cdot \frac{V_{ref}}{V_i} \cdot T_{sf} \cdot \sin \beta \quad (9)$$

where  $\beta$  is the angle between the reference voltage vector  $V_{ref}$  and voltage vector  $V_1$ . In the MSVM Figure 1c) where  $T_{sr}$  is shoot-through time, the STS are evenly assigned to each phase with  $\frac{2}{3}T$  within zero voltage period  $\frac{T_0}{4}$  and  $\frac{1}{3}T$  within active voltage period  $\frac{T_a}{2}$  and  $\frac{1}{3}T$  within active voltage period  $\frac{T_b}{2}$ , 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).

$$T_{sr} = 6.2 \frac{T}{3} = 4T \Rightarrow T = \frac{T_{sr}}{4} \quad (10)$$

And from [15] we have

$$0 < d_o = \frac{T_{sr}}{T_{sf}} < \frac{1}{2} \Rightarrow 0 < T_{sr} < \frac{T_{sf}}{2} \quad (11)$$

Where  $d_o$  is shoot through duty. From (10) and (11) we have

$$0 < T < \frac{T_{sf}}{8} \quad (12)$$

There for, controlling the PDV across the inverter bridge have to found on limited of time  $T$ .

2) DTC-MSVM: The DTC-MSVM are combined from DTC and MSVM, the DTC-MSVM there are features the same With DTC-SVM suchas: fast torque response, low steady state torque ripple, low current distortion, high-performance dynamic characteristics and accuracy, especially in DTC-MSVM, the value of dc-link voltage  $v_i$  can be controlled by regulating STS when DIV sudden change, that it does not affect to SIM control and torque motor. There fore, the DTC-MSVM is the best candidate for HEV applications Figure 2c).

### 2.3. A new algorithm control the PDV across the inverter bridge and SIM due to SFPA, stator flux controller, electromagnetic torque controller, speed controller

All of the transfer functions and controllers parameters PI of electro magnetic torque and stator flux are given in [5] Figure 2c).

When we operate the general DTC-MSVM Figure 2c), All of parameters are always changing such as load torque, IM parameters and DIV. If we use conventional PI controller, two parameters  $K_p$ ,  $K_i$  of PI controller don't change to the continuous variations of those parameters. There fore, on-line tuning algorithms become desirable when high performance, accuracy and robustness are required from the control systems.

The first, PI Controllers parameters  $K_p$ ,  $K_i$  are calculated base on sisotool of Matlab [5], then using SFPA to update  $K_p$ ,  $K_i$  to cope with the continuous parameter variations in non-linear systems.

The PDV and SIM are controlled by SFPA that the two parameters  $K_p$ ,  $K_i$  of conventional PI controller are tuned by using fuzzy inference tuner due to the sudden change of DIV, load torque and stator resistance, respectively. The transient response of PDV and SIM are thus improved with low disturbance for output voltage stabilization in the inverter bridge, high performance, accuracy and robustness Figure 2a) and b).

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 ( $R_s$ ) resistance ( $\Omega$ )	1.115;1.6	14.2;21
Rotor ( $R_r$ ) resistance ( $\Omega$ )	1.083	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 ( $J_m$ ) ( $kgm^2$ )	$2 \cdot 10^{-2}$	$5.5 \cdot 10^{-3}$
Friction factor ( $B_m$ )(N.m.s)	$5.752 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
DC-link peak voltage ( $V_{i,ref}$ )(V)	560	560
DC input voltage( $V_{in}$ )(V)	500,450,400	500,450,400
Speed motor ( <i>or-ref</i> )(rpm)	1500	1490
load torque ( $T_L$ )(N.m)	18,13,8	3,2,1

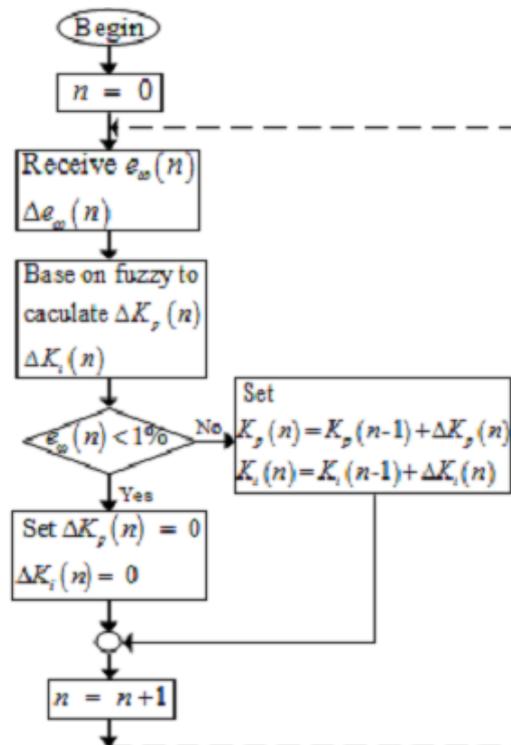


Figure 4. Flowchart of SFP algorithm.

1) SFPA for SIM: When we operate DTC-MSVM that the load torque, stator resistance  $R_s$  are continuous variation. Thus, SIM will be affected by these parameter variations. Therefore, SIM should be controlled by SFPA to improve quality control of non-linear systems such as: decrease error steady state, less overshoot, decrease rise time and faster settling time. In this way, the SIM is more adaptive to the sudden change of the load torque and stator resistance. The response of SIM is thus achieved good reference speed tracking. As a result, we achieve higher robustness and performance of SIM control system Figure 2a) and c).

Following to the fuzzy structure, it includes three blocks generally there are: fuzzification block, fuzzy inference engine that generates the fuzzy rules, a defuzzification block [16]. All of membership function are chosen triangle, the aggregation are used max-min and defuzzification method are used centroid method. In Figure 2a) there are two input signal  $e_w$  and  $de$ . Where  $e$  is the error between reference signal, whereas the output  $de$  is the derivation of  $e_w$ . The linguistic variable levels of two input signal are assigned to five levels such as NB: negative big; N: negative; Z: zero; P: positive; PB: positive big.

Additionally, the first output signal  $K_p$  has three membership functions which the linguistic variable levels of it are assigned to four levels such as Z: zero; P: positive; PM: positive middle; PB: positive big.

Whereas the second output signal  $K_i$  has five membership functions which the linguistic variable levels of it are assigned to five levels such as NB: negative big; N: negative; Z: zero; P: positive; PB: positive big. In Figure 3a) when PID gain increase,  $K_p$  play critical role on rise time,  $K_i$  plays this critical role on error steady state and  $K_d$  only effects on overshoot [12], [17]. Additionally, for some small inertia of systems, they are often used to the PI controller, especially for DTC-MSVM system. Therefore, we want to change  $K_p$ ,  $K_i$  by only change  $\Delta K_p$ ,  $\Delta K_i$  (13).

$$\begin{cases} K_p(n) = K_p(n-1) + \Delta K_p(n) \\ K_i(n) = K_i(n-1) + \Delta K_i(n) \end{cases} \quad (13)$$

Where  $n$  is sample time  $n$ -th, when  $n = 0$  gain PI controller is designed based on [5], there are:

$$K_p(0) = 2J_m \xi \omega_n - B_m \quad (14)$$

$$K_i(0) = J_m \xi \omega_n^2 (2\xi^2 - 1) \quad (15)$$

From Figure 3b) at around  $a_1$ , 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  $\Delta K_p$  is PB,  $\Delta K_i$  is PB Figure 3c) and d).

At around  $b_1$ , the signal control should be tuned small so small error steady state and less overshoot. Consequently,  $K_p$  gain have to be tuned a large, where as  $K_i$  have to be tuned a small. There fore, the following fuzzy rule is given:

If  $e$  is Z and  $de$  is NB, then  $\Delta K_p$  is PB,  $\Delta K_i$  is NB Figure 3c) and d).

Similar for around  $a_2$ ,  $b_2$ ,  $c_2$ ,  $d_2$ . As a result, fuzzy rule are given in Figure 3c) and d).

In Figure 4 show that flowchart of SFP algorithm  $K_p$ ,  $K_i$  Are updated on-line due to limit of  $e\omega$ . Therefore, response of SIM is thus improved, increase robustness and performance of SIM control system.

2) SFPA for PDV: The capacitor voltage ( $V_c$ ) is somewhat equivalent to the PDV of inverter, which the relationship between the PDV ( $V_i$ ) and the capacitor voltage are the non- linear [3]. Additionally, in [8] also show that non-minimum-phase when parameters of ZSI are variations. Consequently, the value of dc link voltage are controlled by controlling the PDV due to SFPA is most suitable for ZSI system.

Base on SFPA have just been analyzed, the PDV is also controlled by SFPA that the two parameters  $K_p$ ,  $K_i$  of conventional PI controller are tuned by using fuzzy inference tuner due to the sudden change of DIV. Fuzzy rule tuning  $K_p$ ,  $K_i$  is the same Figure 3c) and d). The transient response of PDV is thus improved with low disturbance for output voltage stabilization in the inverter bridge Figure 2b).

### 3. SIMULATION AND EXPERIMENTAL RESULTS

There are four main types of motor commonly used in Industry such as: DC motor, synchronous motor, switched reluctance motor and IM but IM is the most advantages such as reliability, controllability, maturity, technological and specially cost. So, IM is the most suitable term for the main requirements of automotive applications, especially the HEV electric propulsion [5], [18]. In this paper, we chose IM for simulation and experimental.

#### 3.1. Simulation results

To verify the validity of the above analysis, Matlab are use to simulate a new algorithm control for DTC-MSVM system. Figure 5a) shows response of DIV, time from 0 to 1s value of DIV is 500 V, 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 Figure 5c) and d). Especially, In Figure 5c) show that PDV is controlled by using two algorithms there are: SFP and PI controller. These results was shown SFPA controller tracking a reference signal ( $V_{i-ref} = 560V$ ) 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 Figure 5b) duty  $d_o$  is also increase to the DIV sudden decrease at 1s 2s. These simulation results are very appropriate with boos characteristic of ZSI.

In addition, in Figure 5e) when the DIV sudden decrease then the current wave form is unvaried. In Figure 5f) THD% is shown current's low total harmonic distortion THD% =3.79%. Therefore, the PDV is controlled by SFPA controller adapt to the DIV change, improves the transient response of PDV, small THD%, increase robust, applying good for speed control induction motor base on the DTC-MSVM control strategy.

In Figure 6c) shown low steady state electromagnetic torque ripple  $\Delta T_e$ . When load torque is sudden change at 1s, 2s Figure 6c), at that time,  $T_e$  is always good tracking to load torque  $T_L$  and SIM is also change due to load torque (6) Figure 6b). When load torque is sudden change at t =1s2s and stator resistance is increase 50% at t =05s speed control of induction motor  $\omega_r$  due to the way SFPA (blue-line) have the settling, overshoot and rise time less than PI controller (red-line) Figure 6b), Figure 6a), respectively. Therefore speed control of induction motor  $\omega_r$  due to SFPA is always tracking ( $\omega_{r-ref}$ =1500rpm) better than PI controller.

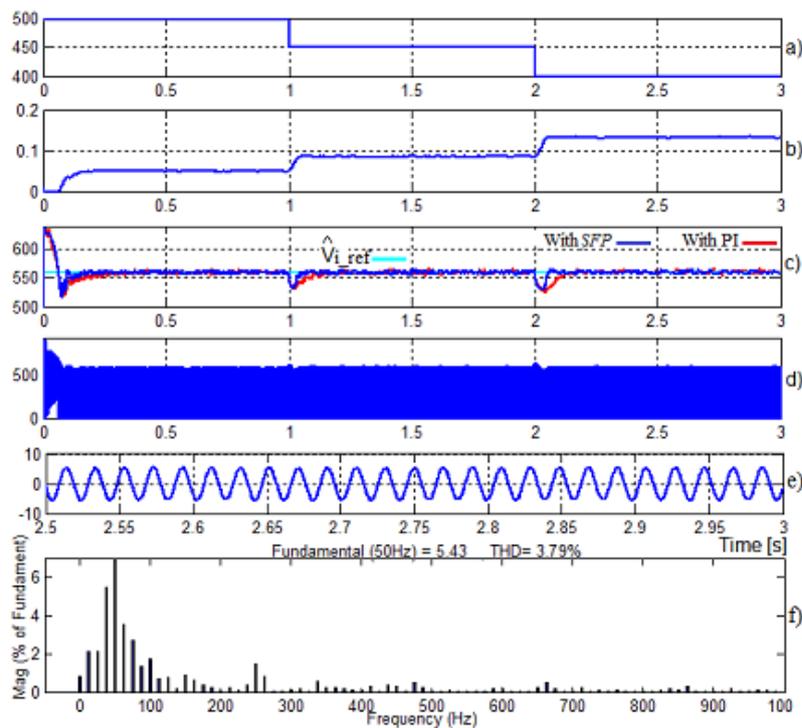


Figure 5. DIV  $V_{in}$  a) Duty  $d_o$  b) PDV  $V_i$  c) And the dc-link voltage  $v_i$  d) The current e) THD% f).

### 3.2. Experimental results

In Figure 7 is figure experiments of the speed control IM 1Hp base on the DTC-MSVM control strategy and applying a new control method for DPV and SIM are proposed. Application DSpace DS1103 communicate with Matlab 2008, using control Desk.V4.1 to display experiment results in Figure 8 that they are shown to DIV  $V_{in}$  sudden decrease at 1s (450V), 2s (400V) Figure 8b). The duty  $d_o$  increase Figure 8a), speed motor is also tracking to  $\omega_{r-ref}$  very good when DIV  $V_{in}$  sudden change Figure 8c). Therefore, experiment results are given in Figure 8 very appropriate simulation results in Figure 5 and Figure 6.

From simulation and experimental results show that characteristics of DTC-MSVM control strategy there are: when DIV decrease 20% but PDV still hold voltage stabilization at 560V, so output voltage still stabilization. Consequently, while stator resistance is increase 50% at t =05s and load torque sudden change, SIM due to the way SFPA is always good tracking to reference SIM.

Additionally, DTC-MSVM control strategy is not also require dead-time protection short circuit at two switches any of the same phase leg increase robust ness which it is the most focus to compare traditional DTC-SVM. Therefore, these characteristics are the most important reasons to the combination of SFPA into DTC-MSVM control strategy for HEV applications.

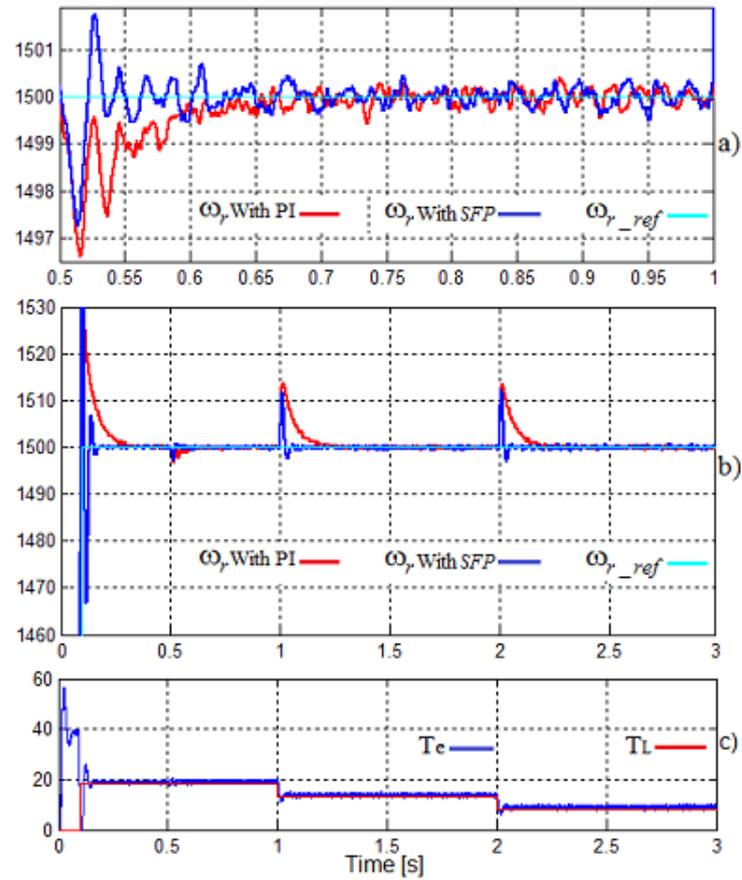


Figure 6. Speed induction motor while  $\omega_r$ . Stator resistance increase 50% at  $t = 0.5s$  a) Load torque decrease at  $t = 1s$  and  $t = 2s$  b) And torque c).

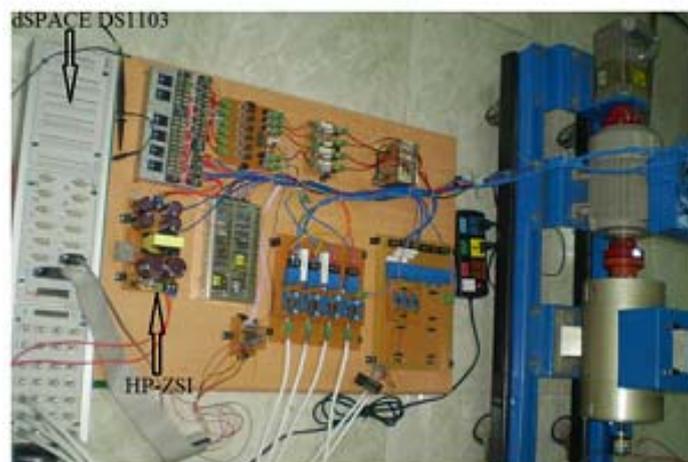


Figure 7. The figure experiments.

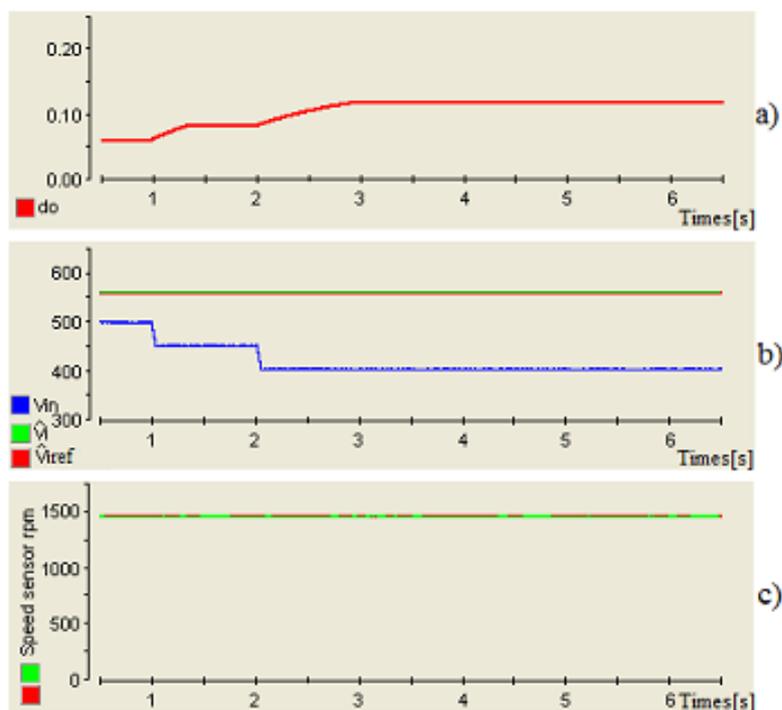


Figure 8. Duty  $d_o$  a) The dc-link peak voltage  $V_i$ , DIV  $V_{in}$  b) And speed motor c).

#### 4. CONCLUSION

Simulation and experimental results are given to verify the proposed a new algorithm to control SIM and PDV by applying SFPA with robust structure and non-linear characteristic. Additionally, SFPA is used to control SIM and PDV are more adaptive to the sudden change of parameters such as load torque, stator resistance and dc input voltage (DIV), respectively. The transient response of SIM and PDV are thus improved with less over shoot, short rise time, small steady-state error and fast settling time, with low disturbance for output voltage stabilization in the inverter bridge. As a result, we achieve higher accuracy and robustness of SIM control system. Therefore, the combination of SFPA into DTC-MSVM control strategy is the best candidate for HEV applications.

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