DESIGN AND ANALYSIS OF FUZZY BASED CONTROL STRATEGY WITH PULSE WIDTH AMPLITUDE MODULATION TECHNIQUE FOR HYBRID VEHICLES

[1] D. Vaishnavi, [2]Mohd.Fayaz pasha,
[1] Department of EEE, Aurora's Polytech Academy, Hyderabad
[2] Department of EEE, Aurora's Scientific Tech & Research Academy, Hyderabad

Abstract: This project introduces a novel control strategy "PWAM" method for HEV/EV motor drive system. This modulation method is quite different from other PWM methods that have been well researched or commonly used for the inverter in HEV/EV system. By using this method, only one phase leg of the inverter is doing switching action for every PWM-carrier period. The boost converter is responsible for generating the fluctuating dc-link voltage, thus needs fast control especially when the output fundamental frequency of the inverter is high. However, the boost converter suffers from low bandwidth due to the existence of a right-half-plane (RHP) zero. A recently introduced single-phase PWM control method, which was first proposed in for grid-connected solar inverters, is found to be promising in motor drive applications.He authors proposed to use multi loop feedback linear zed control strategy to realize the fast control of the boost converter. The outer loop ensures steady-state reference tracking performance and the inner loop provides fast dynamic compensation for system disturbances (including sudden reference or load changes) and improves stability.Then, a multi loop feedback linear zed control strategy is adopted to realize the fast dynamic control requirement.By usingMATLAB/SIMULINK software.

Keywords: Fuzzy logic controller, Boost converter, Hybrid electric vehicle/Electric vehicle, Pulse width amplitude modulation (PWAM)

I.Introduction

In today's HEVs and EVs, high speed motors are used. It uses a boost converter and inverter system. The DC to DC conversion technology has been developingvery rapidly. They are considered to be the most advantageoussupply tools for feeding electronic systems in comparison withlinear power supplies which are simple and have low cost [1]-[2]. Consequently, DC to DC converters have been widelyused in industrial applications such as dc motor drives, computer systems and communication equipments. DC to DCconverters are non-linear in nature. The design of highperformance control for them is a challenge for both thecontrol engineering engineers and power electronicsengineers. In general, a good control for dc–dc convertersalways ensures stability in arbitrary operating condition.

Moreover, good response in terms of rejection of loadvariations, input voltage changes and even parameteruncertainties is also required for a typical control scheme.The boost type DC to DC converters are used inapplications where the required output voltage is higherthan the source voltage.

To turn on and off the inverter switches PWM technique is used. Pulse-width modulation (PWM) is the basis for control in power electronics. Thetheoretically zero rise and fall time of an ideal PWM waveform represents a preferred way of driving modern semiconductor power devices. With the exception ofsome resonant converters, the vast majority of power electronic circuits are controlled by PWM signals of various forms. The rapid rising and falling edges ensurethat the semiconductor power devices are turned on or turned off as fast as practically possible to minimize the switching transition time and the associated switchinglosses.

For DC–DC converters, the PWM reference is a constantwhen the converter operates in a steady state but varies whenever the converter goesthrough a transient.Whereas inverter used this system uses only one phase leg and it is doing PWM switching while the other two phases areclamped to the dc rails. Therefore, the inverter total switching time is reduced to $1/3^{rd}$ that of the conventional SPWMmethod and the total switching loss can be reduced to $1/3^{rd}$ to $1/9^{rd}$. Besides, the inverter dc-link requires muchsmaller capacitance when PWAM method is applied, whichmakes the system more compact and lighter.

The conventional control methodused, such as simple voltage feedback control cannot satisfy therequirement any longer, thus a fast closed-loop control methodis necessary.To reduce the drawback with the previous concept multi loop feedback linearized control strategy is introduced to realize the fast control ofthe boost converter. The outer loop ensures steady-statereference tracking performance and the inner loop provides fastdynamic compensation for system disturbances (includingsudden reference or load changes) and improves stability.

Furthermore, a proportional plus resonant (PR) compensator,revised from traditional PI controller, is added into the outervoltage control loop to achieve zero steady-state error, becausethe dc-link voltage is constantly changing according to the peakoutput voltage envelop, unlike the traditional boost converterthat produces a constant dc voltage.

[1]**Corresponding Author**

II. Boost-Converter-Inverter System Using Pwam Method

A. System configuration

The circuit configuration is shown in Fig.1. 1-kW experiment prototype is built for boost-converter-inverter system using PWAM method. The input is a battery with a voltage range between 100 V and 150 V. The output is a three-phase motor, operating at maximum line-to-line voltage of 230 V rms. For simplicity, simulation and experimental setup uses resistive load instead, and the output frequency varied from 60 Hz to 500 Hz to simulate the working condition of HEV/EV motor drives.
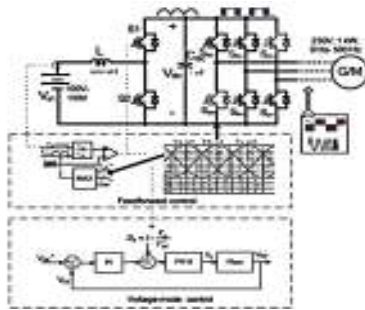
Fig.1. PWAM based boost-converter-inverter system.

B. Operating principle

The principle of PWAM method is to generate a bus voltage with 6ω sinusoidal envelop where ω is the fundamental frequency driving the motor. The peaks of the ripple are corresponding to the peaks of output three-phase line-to-line voltage. In order to generate this ripple, the boost converter needs to be controlled. Only one phase leg is switching at any time for the inverter. The expression for the dc-link voltage is

$$V_{DC} = \begin{cases} V_{peak}\sin(\omega_f t + \pi/3) & (0 \le \omega_f t \le \pi/3) \\ V_{peak}\sin(\omega_f t) & (\pi/3 \le \omega_f t \le 2\pi/3) \\ V_{peak}\sin(\omega_f t - \pi/3) & (2\pi/3 \le \omega_f t \le \pi) \\ V_{peak}\sin(\omega_f t - 2\pi/3) & (\pi \le \omega_f t \le 4\pi/3) \\ V_{peak}\sin(\omega_f t - \pi) & (4\pi/3 \le \omega_f t \le 5\pi/3) \\ V_{peak}\sin(\omega_f t - 4\pi/3) & (5\pi/3 \le \omega_f t \le 2\pi) \end{cases} \quad (1)$$

Where *peak* is the line-to-line peak voltage.

The equation of voltage gain for boost converter is

$$V_{DC} = \frac{1}{1 - D_o} V_{in} \quad (2)$$

Where *D0* is the duty ratio function of boost converter. So in the boost-converter-inverter system,

$$D_o = 1 - \frac{V_{in}}{V_{DC}} \quad (3)$$

is the duty ratio function and can be calculated from (1) and (2).This is used as feed forward control for inverter and boost converter. Fig. 1 shows the control block diagram of PWAM based boost-converter-inverter system [4]. Unlike the traditional SPWM control which requires

to maintain a constant dc-link voltage, the dc capacitor voltage *vC* is fluctuating like a three-phase bridge rectifier waveform in case of the PWAM method. It combines the technique of both pulse width modulation as well as amplitude modulation together. The detailed explanation for the principle and operation can be found in [3]. Although the benefit it brings with reduced switching loss and smaller dc-link capacitor, it also brings a new challenge for the control of boost converter, whether the single loop voltage-mode control can provide fast tracking of 6ω sinusoidal envelop How to improve the transient response of the system.

III. Traditional Closed-Loop Control For Boost Converter

A. Voltage-mode control for boost converter

The voltage-mode closed-loop control for boost converter is using voltage feedback loop to compensate for the error of the feed forward control, which can be seen from the voltage-mode
control from Fig.1. Unfortunately, the transient response of the boost converter is limited by its RHP zero. A bode plot of the RHP zero has the characteristic of a rising 20 dB/dec gain with a 90° phase lag above the zero frequency instead of the 90° phase lead of a left-half-plane (LHP) zero. Therefore, step input response of system containing RHP zero will initially decrease prior to rising and reaching steady state. This causes the sluggish behavior of the boost converter in transient response. For designing controller of the boost converter, the small-signal analysis is usually adopted [6]. Given the small-signal analysis, the value of each variable can be written as the summation of the dc term with its perturbation. The details of deriving the small-signal transfer function of the boost converter is omitted here and readers can refer to [6] for details. The conclusion is directly given. A small-signal control-to-output transfer function for the boost converter is

$$G_{vd}(s) = \frac{\hat{v}_o(s)}{\hat{d}(s)} = G_{d0} \cdot \frac{(1 - \frac{s}{\omega_{RHP}})}{1 + \frac{s}{\omega_0 \cdot Q} + \frac{s^2}{\omega_0^2}}$$

$$where \quad G_{d0} = \frac{V_s}{D^2}, \omega_{RHP} = \frac{(1-D)^2 R}{L} = \frac{D^2 \cdot R}{L}, \omega_0 = \frac{1}{\sqrt{LC}} \cdot D^2,$$

$$Q = D R \sqrt{\frac{C}{L}} = \omega_0 RC \quad (4)$$

For the single-loop control of the boost converter, type I, II and III compensator is widely used. They are characterized by having 1, 2 and 3 poles respectively in the compensation network. In this explanation, type III control has more degrees of freedom, and is more powerful when type I and type II compensator cannot provide enough phase margin to keep the loop stable. The transfer function for type III compensator is where $\omega z1$, $\omega z2$, $\omega p1$, $\omega p1$ are the angular frequency for compensation network zero 1, zero 2, pole 1 and pole 2.

$$C(s) = \frac{k(1+\frac{s}{\omega_{z1}}) \cdot (1+\frac{s}{\omega_{z2}})}{s(1+\frac{s}{\omega_{p1}}) \cdot (1+\frac{s}{\omega_{p2}})} \approx \frac{k(1+\frac{s}{\omega_z})^2}{s(1+\frac{s}{\omega_p})^2}$$

(5)

B. Current-mode control for boost converter

The narrow-gain-bandwidth limitation of voltage-mode control as applied to the non-buck derived converters can be somehow overcome with current-mode control, where an inner current feedback loop is used in addition to the outer voltage feedback loop. The detailed derivation can be found from [5]. The conclusion is directly given here. The control-to-output transfer function for the boost converter with current-mode control is

$$G_v(s) = \frac{F_m * G_{vd}(s)}{1 + T_i(s) - K_r * F_m * G_{vd}(s)}$$

$$where \quad G_{vd}(s) = \frac{\hat{v}_o(s)}{\hat{d}(s)} = G_{d0} \cdot \frac{(1-\frac{s}{\omega_{RHP}})}{1+\frac{s}{\omega_0 \cdot Q}+\frac{s^2}{\omega_0^2}}$$

$$F_m = \frac{1}{(S_n + S_e)T_s} = \frac{1}{m_c S_n T_s} \quad m_c = 1+\frac{S_e}{S_n} \quad K_f = -\frac{T_s R_i}{2L}$$

$$G_{id}(s) = \frac{\hat{i}_L(s)}{\hat{d}(s)} = G_{i0} \cdot \frac{(1+\frac{s}{\omega_{zi}})}{1+\frac{s}{\omega_0 \cdot Q}+\frac{s^2}{\omega_0^2}}$$

(6)

$$H_e(s) = 1+\frac{s}{\omega_n Q_z}+\frac{s^2}{\omega_n^2}$$

$$T_i(s) = F_m * G_{id}(s) * R_i * H_e(s)$$ (7)

Since $T_i(s) \geq 1 - K_r * F_m * G_{vd}(s)$, and neglect the influence of equivalent series resistance, the current-mode control-to-output transfer function for the boost converter can be simplified as: voltage is fluctuating. Therefore, to totally tackle the problem, a feedback linearized control with proportional plus resonant (PR) compensator is then added into the outer voltage regulation
loop to achieve zero steady-state error. The analysis and simulation result is shown in next section.

IV.Fuzzy Logic Controller

A. Introduction

One of the reasons for the popularity of Fuzzy Logic Controllers is its logical resemblance to ahuman operator. It operates on the foundations of a knowledge base which in turn rely upon thevarious if then rules, similar to a human operator [8]. Unlike other control strategies, this issimpler as there is no complex mathematical knowledge required. The FLC requires only aqualitative knowledge of the system thereby making the controller not only easy to use, but alsoeasy to design.

B. Application Areas of Fuzzy Logic Controllers

The fuzzy logic Controllers are basically put to use when [7]:

1) The system is highly non-linear thereby making the making the mathematical modeling of the system very arduous.

2) The analytical form of the system is not provided, instead a linguistic form is provided.

3) The precise identification of the system parameters.

4) The system behavior has a vague characteristic under precisely defined conditions. [7]

5) The conditions themselves are vague.

C. Components of FLC

The inputs to a Fuzzy Logic Controller are the processed with the help of linguistic variableswhich in turn are defined with the aid of membership functions. The membership functions arechosen in such a manner that they cover the whole of the universe of discourse. To avoid anydiscontinuity with respect to minor changes in the inputs, the adjacent fuzzy sets must overlapeach other [9]. Because of a small time constant in Fuzzy Logic Controllers, this criterion is veryimportant in the design of the same.

There are basically three essential segments in Fuzzy Logic Controller viz.

1. Fuzzification block or Fuzzifier.

2. Inference System.
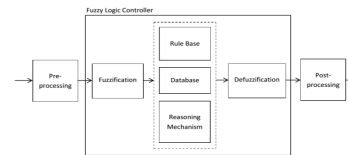
3. Defuzzification block or Defuzzufier.

Fig. 2.Fuzzy Logic Controller Structure

D. Membership function

The design of a Fuzzy Logic Controller requires the choice of Membership Functions. To achieve finer control, the membership functions near the zero regions should be made narrow. Wider membership functions away from the zero regions provide faster response to the system. Hence, the membership functions should be adjusted accordingly. After the appropriate membership functions are chosen, a rule base should be created. It consists of a number of Fuzzy If-Then rules that completely define the behavior of the system. These rules very much resemble the human thought process, thereby providing artificial intelligence to the system. The inputs to the Fuzzy Logic Controller are:

1) Voltage Error (Ve).

2) Change in Error (ΔVe) or derivative of voltage error.

Table.I.Fuzzy Sets and MFs for Input Variable Voltage Error (Ve)

Fig.6. Circuit based simulation for PWAM boost-converter-inverter system with voltage-mode control with *fsw*=20 kHz (a). and *fline*=240 Hz.
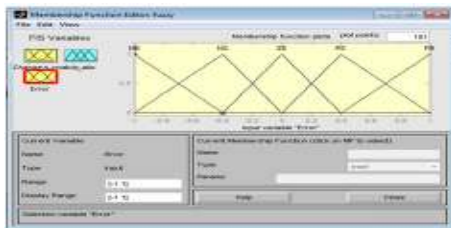
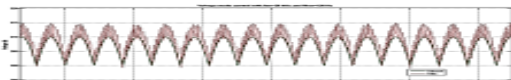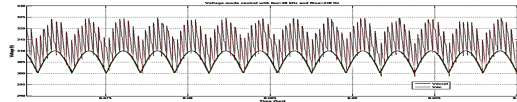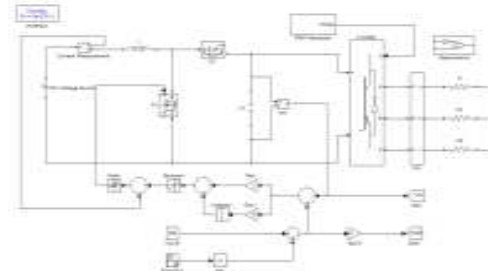Fuzzy rule table:

The Rule Base for deciding the output of the inference system consists of 49 If-Then rules in this case since there are 7 fuzzy sets in each of the inputs.

Table. II. Representing the rule base is as follows

ΔVe \ Ve	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NLM	NM	NMS	NS	ZE
NM	NL	NLM	NM	NMS	NS	ZE	PS
NS	NLM	NM	NMS	NS	ZE	PS	PMS
ZE	NM	NMS	NS	ZE	PS	PMS	PM
PS	NMS	NS	ZE	PS	PMS	PM	PLM
PM	NS	ZE	PS	PMS	PM	PLM	PL
PL	ZE	PS	PMS	PM	PLM	PL	PL

Fig. 7.Simulink model for current-mode control of PWAM boost converter inverter system for *fline*=240 Hz and *fsw*=20 kHz.

Membership Editor:

V. Matlab/Simulink Results
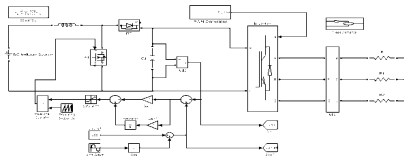
Fig.3 Matlab/Simulink model for PWAM boost-converter-inverter system with voltage-mode control with *fsw*=20 kHz and *fline*=60 Hz
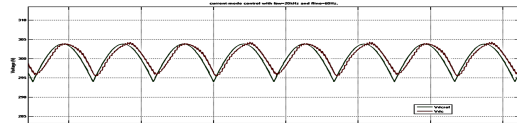

Fig.8. Circuit based simulation for current-mode control of PWAM boost converter inverter system for *fline*=240 Hz and *fsw*=20 kHz.

Fig.4. Circuit based simulation for PWAM boost-converter-inverter system with voltage-mode control with *fsw*=20 kHz and *fline*=60 Hz
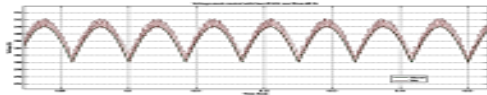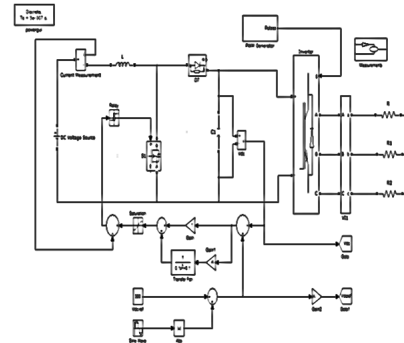

Fig.9. Simulation model of PWAM based boost-converter-inverter system with feedback linearization control for *fline*=240 Hz and *fsw*=20 kHz..

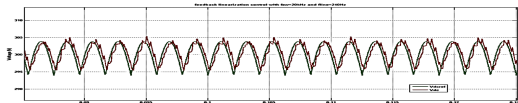Fig. 5.simulation for PWAM boost-converter-inverter system with voltage-mode control with *fsw*=20 kHz and *fline*=120 Hz.

Fig.10. Simulation result of PWAM based boost-converter-inverter system with feedback linearization control for *fline*=240 Hz and *fsw*=20 kHz.
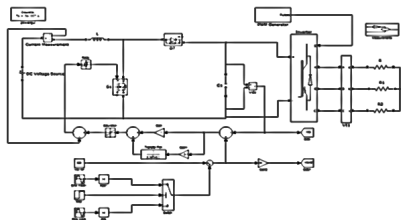
Fig. 11. Simulation model of PWAM based boost-converter-inverter system with feedback linearization control for *fline*changes from 240 Hz to 300 Hz and *fsw*=20 kHz.
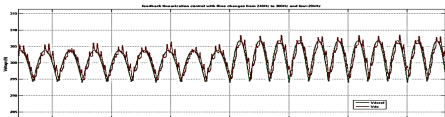

Fig.12. Simulation result of PWAM based boost-converter-inverter system with feedback linearization control for *fline* changes from 240 Hz to 300 Hz and *fsw*=20 kHz.
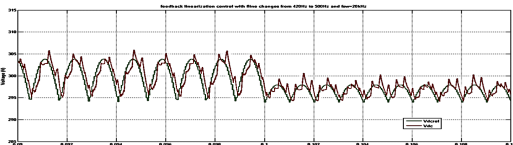

Fig.13. Simulation result of PWAM based boost-converter-inverter system with feedback linearization control for *fline* changes from 420 Hz to 500 Hz and *fsw*=20 kHz.

Fig:14 Simulation wave form of Fuzzy logic control basedPWAM based boost-converter-inverter system with feedback linearization control for *fline*=240 Hz and *fsw*=300 HZ.
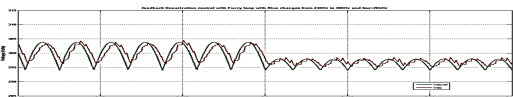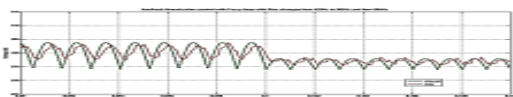

Fig: 15 Simulation wave form of Fuzzy logic control basedPWAM based boost-converter-inverter system with feedback linearization control for *fline*=420HZ and *fsw*=500 HZ

VI. Conclusion

In this paper, a fuzzy based control strategy for boost converter/inverter for hybrid vehicles is implemented. The system with its control strategy is especially suitable for HEV/EV motor drives. The PWAM method requires only one phase leg to do PWM switching action. Thus, switching loss can be greatly reduced by more than 2/3. Furthermore, unlike the conventional inverter system, which requires relatively larger dc-link capacitor to absorb ripple and keep voltage stable, the PWAM based

system with fast control needs much smaller capacitance since dc-link voltage is fluctuating. This is a special feature of PWAM method. Fast control of the boost converter will make sure the dc-link voltage tracks well with 6ω sinusoidal envelops required by the PWAM method. The multi loop feedback linearized control strategy provides fast dynamics and accurate control of the boost converter and PR controller for outer voltage loop guarantees zero steady-state error. Fuzzy logic control based system makes the system more efficient and reliable and also it will increase the overall system performance.

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