

PWAM BASED BOOST CONVERTER/INVERTER WITH FUZZY LOGIC CONTROLLER FOR HEV/EV MOTOR DRIVE APPLICATIONS

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ABSTRACT: This project initiates a novel control strategy "PWAM" based boost converter/inverter fed fuzzy logic controller for HEV/EV motor drive applications. This modulation method is pretty unusual from other pulse width modulation methods that have been well examined or universally used for the inverter in HEV/EV system. By using this technique, only one phase leg of the inverter is doing switching action for each PWM-carrier period. The boost converter is accountable for generating the unpredictable dc-link voltage, thus desires quick management particularly when the output fundamental frequency of the inverter is high. However, the boost converter undergoes from short bandwidth due to the continuation of a right-half-plane (RHP) zero. A newly introduced single-phase PWM control method, which was first proposed in for grid-connected solar inverters, is established to be promising in motor drive applications. The outer loop guarantees steady-state reference tracking concert and the inner loop affords fast dynamic compensation for system conflict (including sudden reference or load changes) and improves stability. The proposed concept can be verified and simulated using MATLAB/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 developing very rapidly. They are considered to be the most advantageous supply tools for feeding electronic systems in comparison with linear power supplies which are simple and have low cost [1]-[2]. Consequently, DC to DC converters have been widely used in industrial applications such as dc motor drives, computer systems and communication equipments. DC to DC converters are non-linear in nature. The design of high performance control for them is a challenge for both the control engineering engineers and power electronics engineers. In general, a good control for dc-dc converters always ensures stability in arbitrary operating condition. Moreover, good response in terms of rejection of load variations, input voltage changes and even

parameter uncertainties is also required for a typical control scheme. The boost type DC to DC converters are used in applications where the required output voltage is higher than 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. Theoretically zero rise and fall time of an ideal PWM waveform represents a preferred way of driving modern semiconductor power devices. With the exception of some resonant converters, the vast majority of power electronic circuits are controlled by PWM signals of various forms. The rapid rising and falling edges ensure that the semiconductor power devices are turned on or turned off as fast as practically possible to minimize the switching transition time and the associated switching losses.

For DC-DC converters, the PWM reference is a constant when the converter operates in a steady state but varies whenever the converter goes through a transient. Whereas inverter used this system uses only one phase leg and it is doing PWM switching while the other two phases are clamped to the dc rails. Therefore, the inverter total switching time is reduced to $1/3^{\text{rd}}$ that of the conventional SPWM method and the total switching loss can be reduced to $1/3^{\text{rd}}$ to $1/9^{\text{rd}}$. Besides, the inverter dc-link requires much smaller capacitance when PWAM method is applied, which makes the system more compact and lighter.

The conventional control method used, such as simple voltage feedback control cannot satisfy the requirement any longer, thus a fast closed-loop control method is necessary. To reduce the drawback with the previous concept multi-loop feedback linearized control strategy is introduced 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.

Furthermore, a proportional plus resonant (PR) compensator, revised from traditional PI controller, is added into the outer voltage control loop to

achieve zero steady-state error, because the dc-link voltage is constantly changing according to the peak output voltage envelop, unlike the traditional boost converter that produces a constant dc voltage.

II. PWAM BASED BOOST CONVERTER/INVERTER SYSTEM

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.

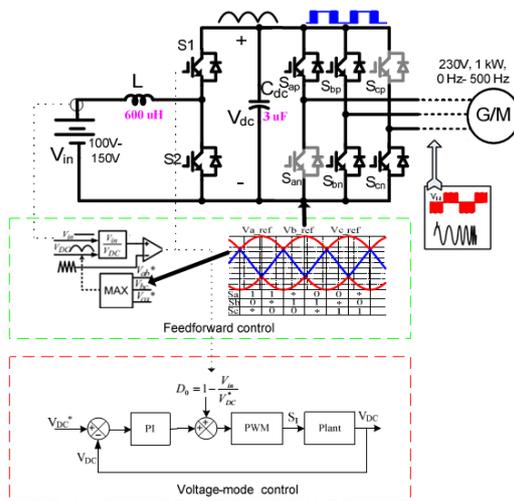


Fig.1. PWAM based boost-converter-inverter system.

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

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

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

The equation of voltage gain for boost converter is

$$V_{dc} = \frac{1}{1-D_0} V_{in} \quad (2)$$

Where D_0 is the duty ratio function of boost converter. So in the boost-converter-inverter system,

$$D_0 = 1 - \frac{V_{in}}{V_{dc}} \quad (3)$$

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 v_c 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. CONVENTIONAL CLOSED-LOOP CONTROL FOR BOOST CONVERTER

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

$$G_{vd}(s) = \frac{\hat{v}_o(s)}{d(s)} = G_{a0} \cdot \frac{(1 - \frac{s}{\omega_{zHP}})}{1 + \frac{s}{\omega_b \cdot Q} + \frac{s^2}{\omega_b^2}}$$

where $G_{a0} = \frac{V_c}{D^2}$, $\omega_{zHP} = \frac{(1-D)^2 R}{L} = \frac{D^2 \cdot R}{L}$, $\omega_b = \frac{1}{\sqrt{LC}} \cdot D^2$,
 $Q = DR \sqrt{\frac{C}{L}} = \omega_b RC$ (3)

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 ω_{z1} , ω_{z2} , ω_{p1} , ω_{p2} are the angular frequency for compensation network zero 1, zero 2, pole 1 and pole 2.

$$C(s) = \frac{k(1 + \frac{s}{\omega_{z1}}) \cdot (1 + \frac{s}{\omega_{z2}})}{s(1 + \frac{s}{\omega_{p1}}) \cdot (1 + \frac{s}{\omega_{p2}})} \approx \frac{k(1 + \frac{s}{\omega_z})^2}{s(1 + \frac{s}{\omega_p})^2}$$
 (4)

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 $G_{vd}(s) = \frac{\hat{v}_o(s)}{d(s)} = G_{a0} \cdot \frac{(1 - \frac{s}{\omega_{zHP}})}{1 + \frac{s}{\omega_b \cdot Q} + \frac{s^2}{\omega_b^2}}$

$$F_m = \frac{1}{(S_n + S_c)T_i} = \frac{1}{m_c S_n T_i} \quad m_c = 1 + \frac{S_c}{S_n} \quad K_r = -\frac{T_r R_i}{2L}$$

$$G_{vd}(s) = \frac{\hat{i}_L(s)}{d(s)} = G_{i0} \cdot \frac{(1 + \frac{s}{\omega_{zi}})}{1 + \frac{s}{\omega_b \cdot Q} + \frac{s^2}{\omega_b^2}}$$
 (5)
$$H_e(s) = 1 + \frac{s}{\omega_n Q_z} + \frac{s^2}{\omega_n^2}$$

$$T_i(s) = F_m * G_{vd}(s) * R_i * H_e(s) \quad (6)$$

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

Introduction

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

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.

Components of FLC

The inputs to a Fuzzy Logic Controller are the processed with the help of linguistic variables which in turn are defined with the aid of membership functions. The membership functions are chosen in such a manner that they cover the whole of the universe of discourse. To avoid any discontinuity with respect to minor changes in the inputs, the adjacent fuzzy sets must overlap each other [9]. Because of a small time constant in Fuzzy Logic Controllers, this criterion is very important in the design of the same.

There are basically three essential segments in Fuzzy Logic Controller viz. Fuzzification block or Fuzzifier, Inference System, Defuzzification block or Defuzzifier.

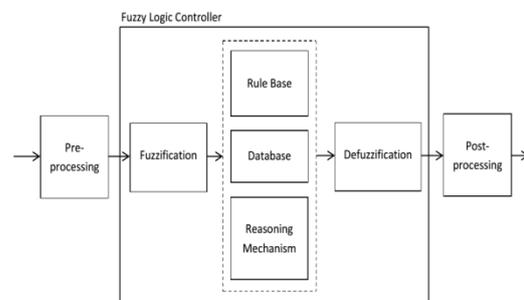


Fig.2 Fuzzy Logic Controller Structure

Fuzzification Block or Fuzzifier

The first step towards designing a Fuzzy Logic Controller is choosing appropriate inputs which will be fed to the same. These input variables should be

such that, they represent the dynamical system completely. Then the function of the Fuzzifier comes into picture. As discussed before, instead of using numerical variables, fuzzy logic uses linguistic variables for processing information. But since the inputs to the FLC are in the form of numerical variables (or in other words, crisp sets), they need to be converted into linguistic variables. This function of converting these crisp sets into fuzzy sets (linguistic variables) is performed by the Fuzzifier. The fuzzification technique involves outlining the membership functions for the inputs. These membership functions should cover the whole universe of discourse and each one represents a fuzzy set or a linguistic variable. The crisp inputs are thus transformed into fuzzy sets. Triangular MF, Trapezoidal MF, Bell MF, Generalized Bell MF or Sigmoidal MF [10] can be used. Even a hybrid of any of the above Membership Functions can be used for fuzzification.

MATLAB/SIMULINK RESULTS

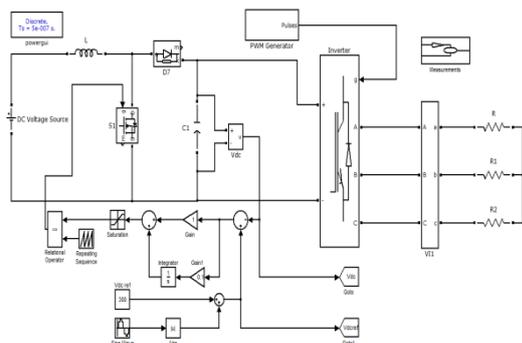


Fig.3 Matlab/Simulink model for PWAM boost-converter-inverter system with voltage-mode control

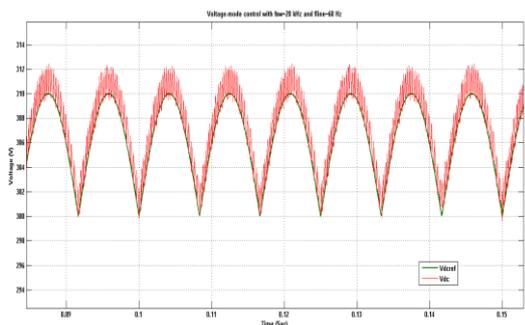


Fig. 4. Output wave form of $f_{sw}=20$ kHz and $f_{ine}=60$ Hz PWAM boost-converter-inverter system with voltage-mode control

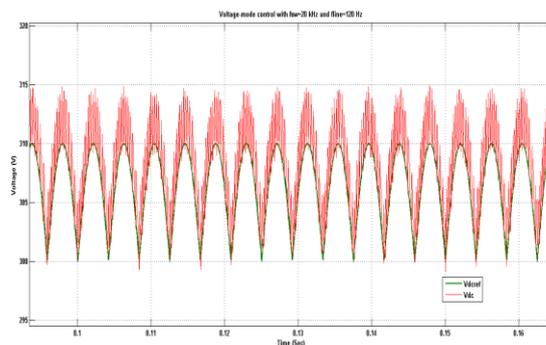


Fig. 5. Output wave form of $f_{sw}=20$ kHz and $f_{ine}=120$ Hz PWAM boost-converter-inverter system with voltage-mode control

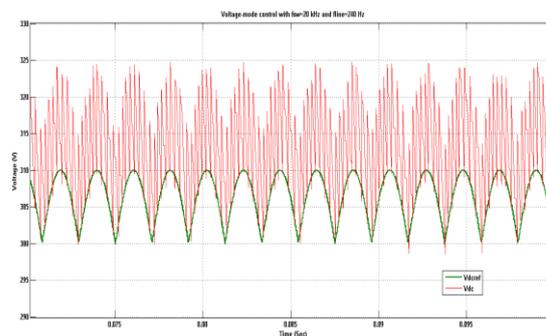


Fig. 6. Circuit based simulation for PWAM boost-converter-inverter system with voltage-mode control with $f_{sw}=20$ kHz (a) and $f_{ine}=240$ Hz.

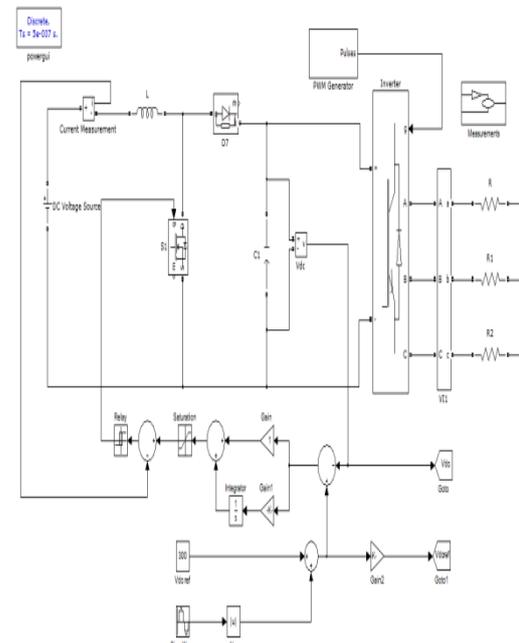


Fig. 7. Output wave form of current-mode control of PWAM boost converter inverter system for $f_{ine}=240$ Hz and $f_{sw}=20$ kHz.

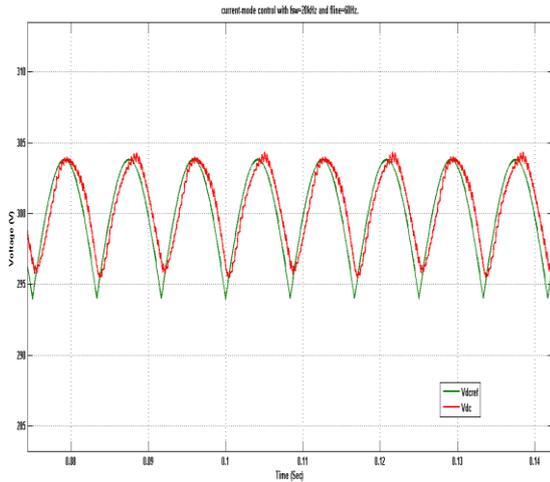


Fig. 8. Output waveform of current-mode control of PWM boost converter inverter system for $f_{fine}=240$ Hz and $f_{sw}=20$ kHz.

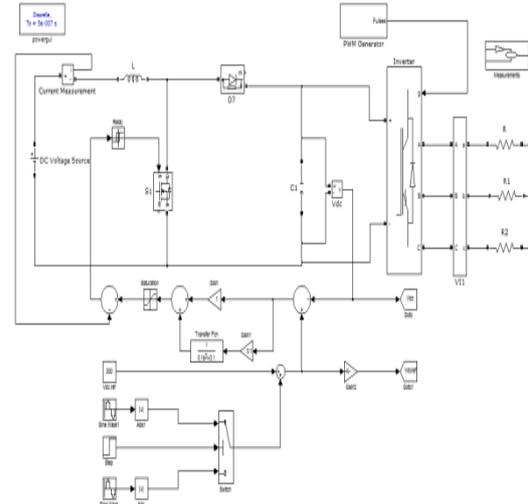


Fig. 11. Simulation model of PWAM based boost-converter-inverter system with feedback linearization control for f_{fine} changes from 240 Hz to 300 Hz and $f_{sw}=20$ kHz.

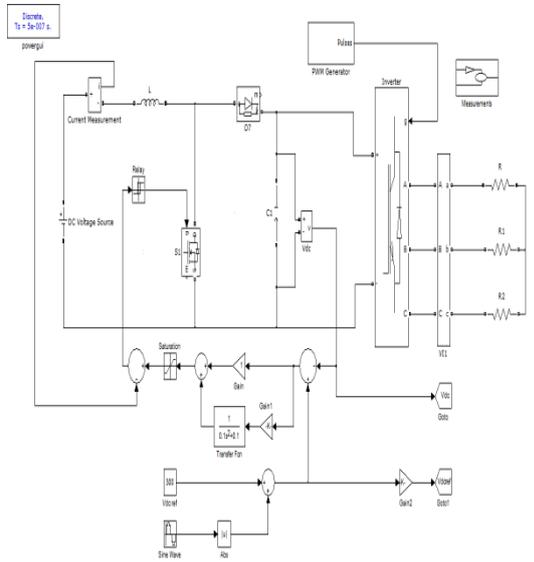


Fig. 9. Simulink model of PWAM based boost-converter-inverter system with feedback linearization control for $f_{fine}=240$ Hz and $f_{sw}=20$ kHz.

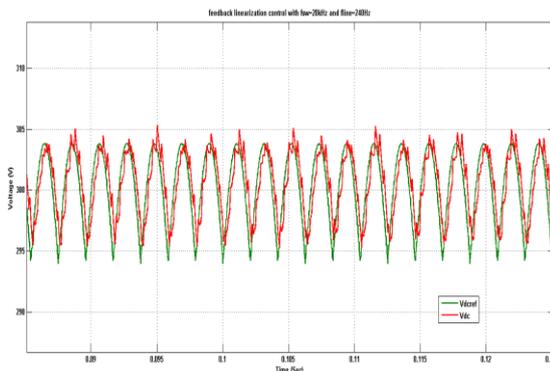


Fig.10. Output waveform of PWAM based boost-converter-inverter system with feedback linearization control for $f_{fine}=240$ Hz and $f_{sw}=20$ kHz.

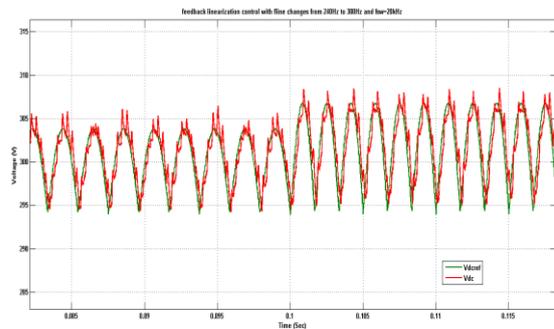


Fig. 12. Output waveform of PWAM based boost-converter-inverter system with feedback linearization control for f_{fine} changes from 240 Hz to 300 Hz and $f_{sw}=20$ kHz.

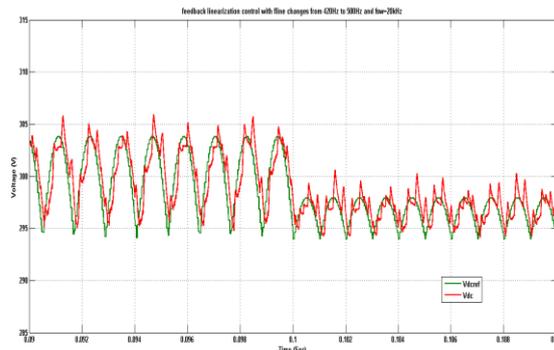


Fig. 13. Output waveform of PWAM based boost-converter-inverter system with feedback linearization control for f_{fine} changes from 420 Hz to 500 Hz and $f_{sw}=20$ kHz.

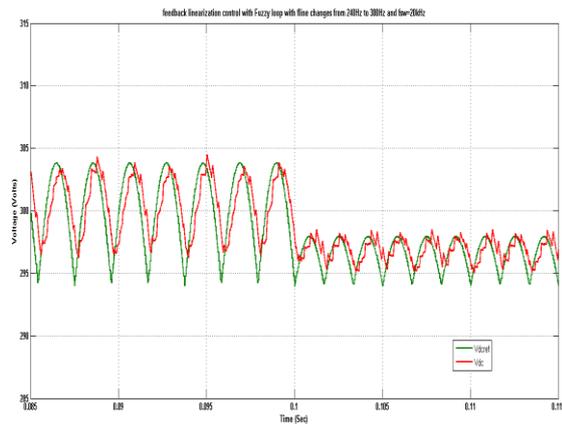


Fig:14 Simulation wave form of Fuzzy logic control basedPWAM based boost-converter-inverter system with feedback linearization control for $f_{line}=240$ Hz and $f_{sw}=300$ HZ

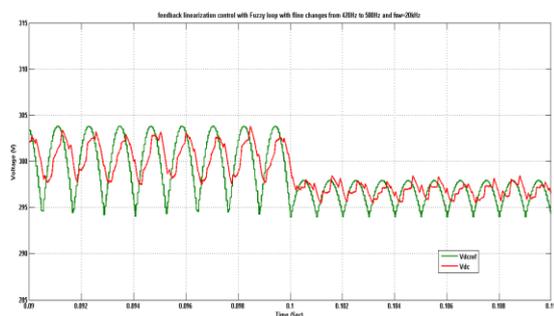


Fig:14 Simulation wave form of Fuzzy logic control basedPWAM based boost-converter-inverter system with feedback linearization control for $f_{line}=420$ HZ and $f_{sw}=500$ HZ

CONCLUSION

In this project, a PWAM based boost converter/inverter fed FLC hybrid vehicles applications 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 envelopes 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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