Chopper-Based Real-Time Load Emulator with Feed-Forward and Hysteresis Current Controller

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Abstract :

Nowadays, the usage of load emulators, is the best method for implementation and analysis of different electrical load change scenarios in laboratories. This paper presents an improved programmable load emulator which can emulate both reference active and reactive power simultaneously. The proposed control system can track the dynamic load changes rapidly and accurately in addition to pulse change emulation. So it is completely suitable for both dynamic and transient stability analysis. The emulator topology is made up of an inverter and a buck converter. Simple PI controller because of its coefficients dependence to operating point is not suitable especially for this application in which the operating point is constantly changing in a wide range. The usage of a Feed-Forward controller for grid side inverter increases the DC bus voltage stability and on the other hand the usage of the hysteresis current controller for buck converter improves the rate and accuracy of the reference active power tracking. Simulation results in SIMULINK verify the performance of the proposed control system.

Keywords: Real-time Load Emulator, Feed-Forward Controller, Hysteresis Current Controller, LCL filter.

Submission date : 31 , 10 , 2016

Acceptance date : 09 , 09 , 2017

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1. Introduction

Appearance of the concepts such as microgrid and smart grid beside increasing laboratory investigations which consist of different load and generation change scenarios lead to the appearance of emulation concept. An Emulator is a power electronic converter which can emulate different kinds of electrical load such as induction motor or a heater. Power electronic converters based on the inverters and DC-DC converters using control loops which are able to track reference values of active and reactive power, current and voltage. So for example a real time load emulator according to time-domain active and reactive power curves of the load furthermore hardware in the loop is one of the other applications of load emulators [1-2].

Till now several platforms are presented for real time emulation which some of them considered the load-generator emulation simultaneously [3]. [4] presented a real time load emulator with an optimal control system including back to back inverter with a common DC bus. The grid side inverter adjust the active and reactive power according to the reference values. Other inverter controls its DC and AC bus voltages and refers active power to the grid again which called as regeneration process. [5] presented dual active bridge topology for a real time load emulator. A DC-DC converter with high frequency transformer was used in this topology. Other researches in this case are related to software investigations around the load model such as nonlinear load emulation [6]. [7] proposed a real time emulator for simulation of load values measured by smart meters. The proposed topology consists of an inverter, a buck converter and a resistor. In this structure, grid side inverter controls the reactive power and DC link voltage separately. Buck converter also controls the active power by resistor voltage adjustment. The elimination of extra five semiconductor switches and more simple control system are advantages of this topology in comparison to the conventional back to back inverter topology. Regeneration ability of load emulator are not important in comparison to construction cost in laboratory cases because of short time usage and low power scale. The proposed control system of [7] is a simple PI controller. This control system need to some modification for more power tracking speed and accuracy and also DC link voltage stability in different operation.

In this paper, the inverter controller and the Buck converter controller are considered separately. A Feed-Forward controller is presented for grid side inverter due to improve the DC link voltage stability in different operation points. On other hand the usage of the simple PI current controller has not enough performance in tracking of the fast changes in active power. PI performance depends on its coefficients optimal tuning which is mainly dependent upon the operation point. This defect can be improved considerably by using of hysteresis current controller instead of PI controller. Feed-Forward and Hysteresis controller is introduced respectively in section II and III. The proposed control system is presented in section IV and finally in section V simulation results in SIMULINK software verify the proposed control system performance for both pulse and dynamic load changes in comparison to the conventional PI controller.

2. Proposed Topology and Control System

2.1. Circuit Topology

The circuit topology of real-time load emulator is depicted in Fig1. This circuit is connected to the three-phase grid and plays the role of a programmable three-phase load. It can sink predetermined active and reactive power profiles from the grid. The circuit of Fig 1 is made up of four parts:

- Three-phase PWM inverter
- LCL filter
- Buck converter
- Resistive load

Buck converter sets the active power to the reference value by resistor voltage control. A hysteresis current controller is responsible of this control. The grid-side inverter gets the reference values of reactive power and DC bus voltage and set them by a Feed-Forward current controller. The adjustment of DC bus voltage means the providence of required active power of the buck converter.

The circuit topology of emulator is gained by addition of a LCL filter in DC bus of [7] emulator topology. This LCL filter can play the role of current-voltage stabilizer which its advantages demonstrate in simulation results of section IV. The attenuation at the switching frequency can be determined by plotting the bode plot of the transfer function:

$$\frac{i_L}{i_{DC}} = \frac{1}{1 + C.L_2 s^2} \tag{1}$$

Where the grid impedance Zs has been neglected. In the case of the 3 kW inverter having Ud = 350 V, m =0.93, an LCL filter having a resonance frequency of 4.25 kHz has been designed. The filter transfer function is expressed in (2) [8-9].

$$G_f(s) = \frac{-i_{DC}}{V_{in}} = \frac{1}{L_i s} \frac{(s^2 + z_{LC}^2)}{(s^2 + \omega^2)} \tag{2}$$

Where z_{LC} and ω can be expressed by (2) and (3) respectively.

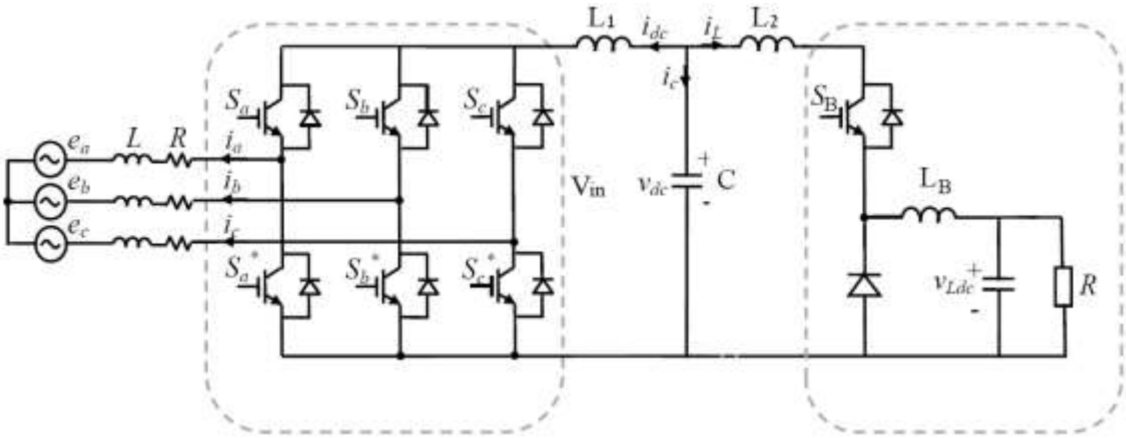

Fig. 1. Emulator topology

$$z_{LC}=\frac{1}{L_2C} \tag{3}$$

$$\omega=\frac{(L_1+L_2)z_{LC}^2}{L_1} \tag{4}$$

Also L_B must be designed so that i_{L_B} remains in CCM mode with respect to the load current.

2.2. Proposed Control System

The proposed control system is depicted in Fig 2. This control system consists of two parts including:

- Grid-side inverter control (left side of Fig 2)
- Buck converter control (right side of Fig 2)

Grid-side inverter control system tries to fix the reactive power and DC bus voltage to their reference values. Buck converter control system tries to fix the active power to its reference value. They are explain more in the following.

2.2.1. Grid-side Inverter Control

The aim of this system is generation of PWM switching pulses for grid-side inverter with the aim of reactive power reference tracking and DC bus voltage fixation in reference value. In dq0 frame i_d^{ref} and i_q^{ref} can be used to control active and reactive power separately. DC bus voltage is related to active power so as shown in Fig 2, DC bus voltage error passing through a PI lead to the calculation of i_d^{ref} .

On other hand Reactive power reference value can be converted to i_q^{ref} as:

$$i_q^{ref}=f(Q^{ref})=\frac{3e_q.i_d-2Q^{ref}}{3e_d} \tag{5}$$

Available i_d^{ref} and i_q^{ref} can be used in a traditional current controller system for generation of PWM pulses but usage of a feed-forward control system is more advantageous.

As shown in fig 2, Feed-Forward controller gets the values of $i_d, i_q, i_d^{ref}, i_q^{ref}, e_d$ and e_q as its inputs and generates v_d^{cont} and v_q^{cont} for PWM switching. The structure of Feed-Forward controller will express completely in section IV.

2.2.2. Buck Converter Control

Hysteresis current controller is used for buck converter switching. Input current of buck converter (i_{DC}) is considered as control variable. i_{DC}^{ref} is determined corresponding to P_{ref} as:

$$i_{DC}^{ref}=f(\mathrm{P}_{ref})=\frac{\mathrm{P}_{ref}}{V_{DC}} \tag{6}$$

The difference of measurement and reference values of i_{DC} is limited among certain upper and lower bands in hysteresis current controller. More details of this method are presented in next section.

3. Hysteresis Current Controller

Current controlled PWM inverters are widely used in high performance AC drives because they offer substantial advantages in eliminating stator dynamics in those systems. The main objective of current controller is to force the load current vector according to reference current trajectory. The performance of converter system is mainly dependent upon the type of current control technique used. In current controller load currents are measured and compared with reference currents, the errors are used as an input to the PWM modulator, which provides inverter switching signals.

In a hysteresis controller, the hysteresis comparators are used to impose hysteresis or hysteresis around the reference current [10]. Among all current control techniques, the hysteresis controller is widely used because of its simplicity of implementation and fast response current loop. This method does not need any knowledge of load parameters. However, the main disadvantage is the variation of switching frequency during load parameter variation of fundamental period.

The proportional integral (PI) current control scheme employs a free-running fixed-frequency carrier signal resulting in a fixed-frequency inverter operation and a well-defined output current harmonics. Typical advantages of such a scheme include absence of the effect of DC-side ripple on the inverter load side waveforms, fixed inverter switching frequency, free running carrier operation and instantaneous takeover of current control.

In this control strategy the measured load currents are compared with the references using hysteresis comparators. Each comparator determines the switching state of the corresponding inverter leg (Sa, Sb and Sc) such that the load currents are forced to remain within the hysteresis band called as lower band and higher band. Based on the band, there are two types of current controllers, namely, fixed band and sinusoidal band hysteresis current controller. Fixed band current controller is considered in this study.

4. Feed-Forward Control

The classical PI current control strategy with voltage feed- forward [11] is depicted in Fig.3 and the new proposed control strategy in Fig. 2.

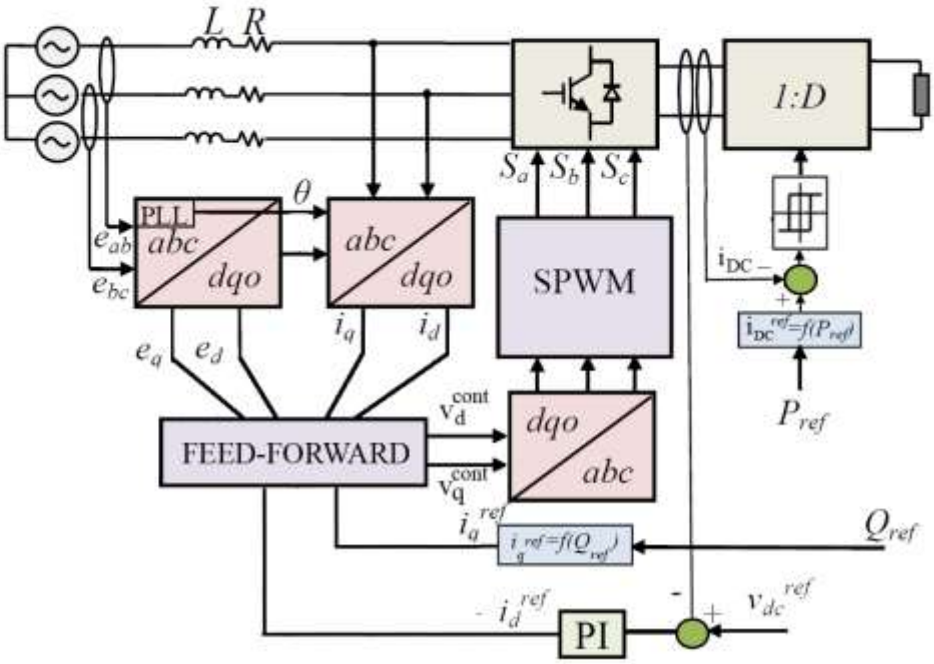

Fig. 2. Proposed control system

Where u_i^* is the inverter voltage reference and i_i^* is the inverter current reference. The PI current controller $G_{PI}(s)$ is defined as:

$$G_{PI}(s) = K_P + \frac{K_I}{s} \tag{7}$$

The PI controller is not able to track a sinusoidal reference without steady-state error. In order to get a good dynamic response, a grid voltage feed-forward current control is used, as depicted in Fig. 3. A processing delay typical equal to T_S for PWM inverters is introduced in $G_d(s)$. $G_f(s)$ is the same filter transfer function which was expressed in (2).

The detail structure of the proposed Feed-Forward controller which is presented in section II is depicted in Fig 4 and 5 respectively for d and q axis control.

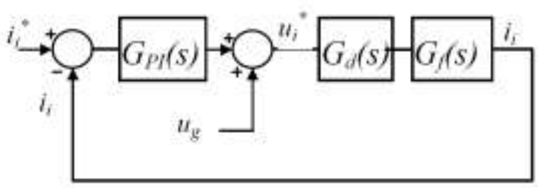

Fig. 3. Feed-Forward current control loop

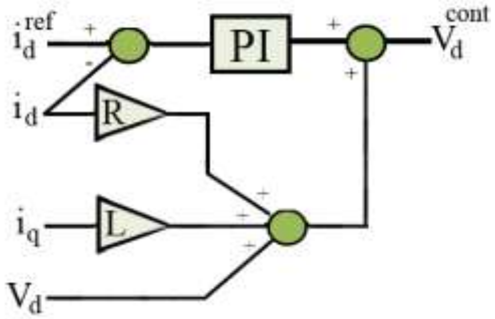

Fig. 4. Vd generating in the proposed control system

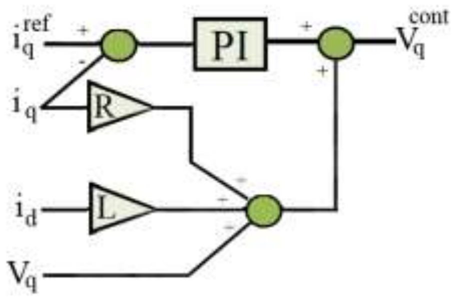

Fig. 5. Vq generating in Proposed Control System

R and *L* parameters are total per unit resistance and inductance of the grid from point of inverter view respectively. As shown in Fig 5 and 6, feed-back current of other axis is considered in this structure in addition to feed-forward voltage. This feedback current of other axis is required because active and reactive power control in dq0 frame is not completely independent. Also feed-forward control idea [10-11] can highly help to the stabilization of DC bus voltage and robustness of the active and reactive power exchange. Also feed-forward control decrease the control system sensitivity to PI coefficients. In next section PI controller design is explained.

4.1. PI Controller Design

PI coefficients design needs to the system model. Inverter tries to regulate DC bus voltage so buck converter modeling is not needed. Inverter can be modeled as a gain. Differential equation of the system in d and q axis:

$$L.\frac{di_{Ld}}{dt} = V_{Ld} - Ri_{Ld} \tag{8}$$

$$L.\frac{di_{Lq}}{dt} = V_{Lq} - Ri_{Lq} \tag{9}$$

In which i_L is inductor current and i_L is:

$$V_{Ld} = V_{invd} - V_{Sd} - \omega L i_q \tag{10}$$

$$V_{Lq} = V_{invq} - V_{Sq} - \omega L i_d \tag{11}$$

Using Laplace transformation:

$$\frac{i_{Ld}(s)}{V_{Ld}(s)} = \frac{1}{Ls+R} \tag{12}$$

PI controller can be presented as:

$$K_P + \frac{K_I}{s} \tag{13}$$

So in a closed loop system total transfer function has a second order form as:

$$T(s) = \frac{K_P s + K_I}{Ls^2 + (\mathrm{R}+\mathrm{K}_P)\mathrm{s} + \mathrm{K}_I} \tag{14}$$

For this second-order system:

$$K_P = 2L\zeta\omega_n + R$$

$$K_I = L\omega_n^{\ 2}$$

ζ and ω_n are damping factor and natural frequency of the second order system. To choose an appropriate value for *L* and *R* also should note this point.

5. Simulation Results

In this section the simulation results of the proposed emulator in MATLAB/SIMULINK software are presented. The circuit topology is the same that was presented before in the section III which is connected to a three-phase grid. Operation conditions and designed values of the circuit parameters are listed in Table 1.

Table 1. Operation conditions and selected parameters

Parameter	Value	Attribute
V_{DC}	500	DC bus Voltage(V)
e_s	400	Line to line grid voltage(V)
R	480	grid Resistance(mΩ)
L	12	grid Inductance(mH)
C	1200	DC bus Capacitor(uF)
L_1	2	Left LCL Inductance(mH)
L_2	2	Right LCL Inductance(mH)
f_s	20	Switching Frequency(kHz)
f	50	Grid Frequency(Hz)
L_B	3	Buck converter Inductance(mH)
C_B	1200	Buck converter capacitance(uF)
R	30	Resistive load(mΩ)

During this simulations the emulator response to these three cases are studied:

- Constant reference power
- Pulse load change
- Dynamic load change

In each scenario the DC bus voltage stability and power tracking ability of the proposed control strategy for emulator is evaluated in comparison to the conventional PI controller.

5.1. Constant Reference Power

In this scenario supposing that reference values of active and reactive power set to 1500W and 500Var respectively. The measured values of the emulator active and reactive power using proposed control strategy are plotted in Fig 6 and 7 respectively by red color and reference value by black color. On other hand the same measurements for conventional PI controller are shown in Fig 8 and 9 by red color and reference by black color. The comparison of these two figures shows the greater performance of the proposed control system in accuracy of emulation.

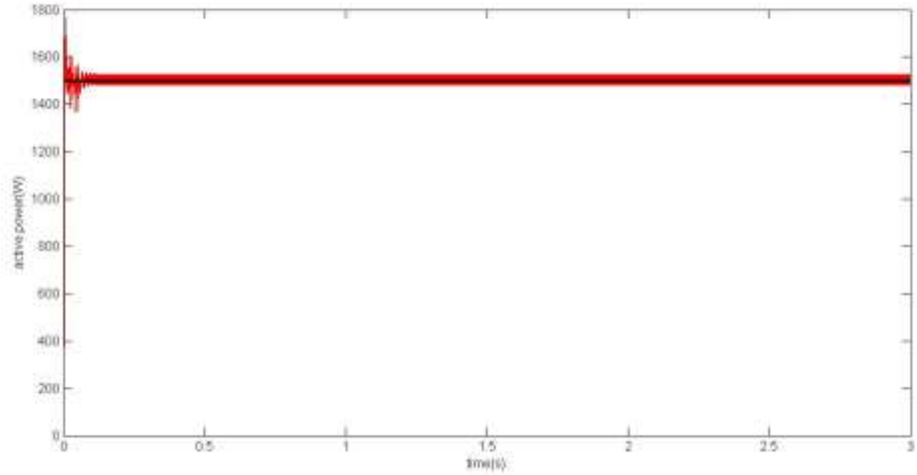

Fig. 6. Active power emulation with constant reference by proposed control system

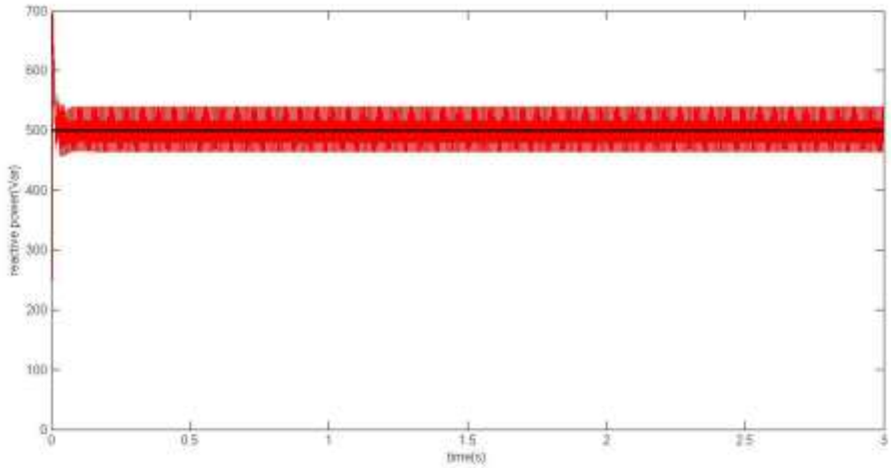

Fig. 7. Reactive power emulation with constant reference by proposed control system

5.2. Dynamic Load Change

Fast dynamic response is one of the most important characteristics of an emulator. In this scenario supposing a periodic triangular reference for active power of emulator as shown in Fig 12 and 13 by black color, the measured values of the emulator power using the proposed control strategy and the conventional PI controller are plotted respectively in Fig 12 and 13 by red color. The response rate and accuracy of the proposed control system is considerably more than conventional PI current controller.

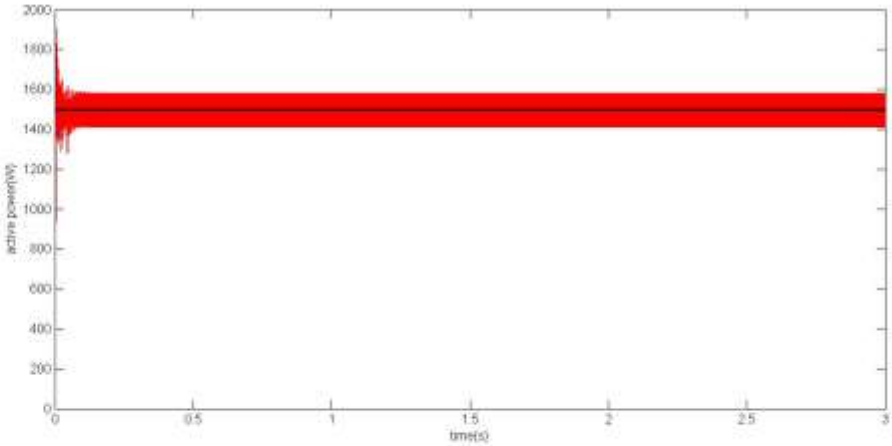

Fig. 8. Active power emulation with constant reference by conventional PI current controller

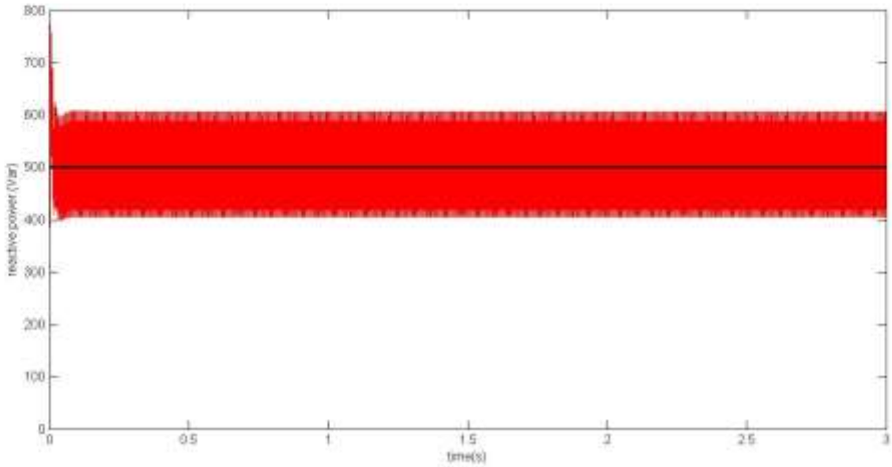

Fig. 9. Reactive power emulation with constant reference by conventional PI current controller.

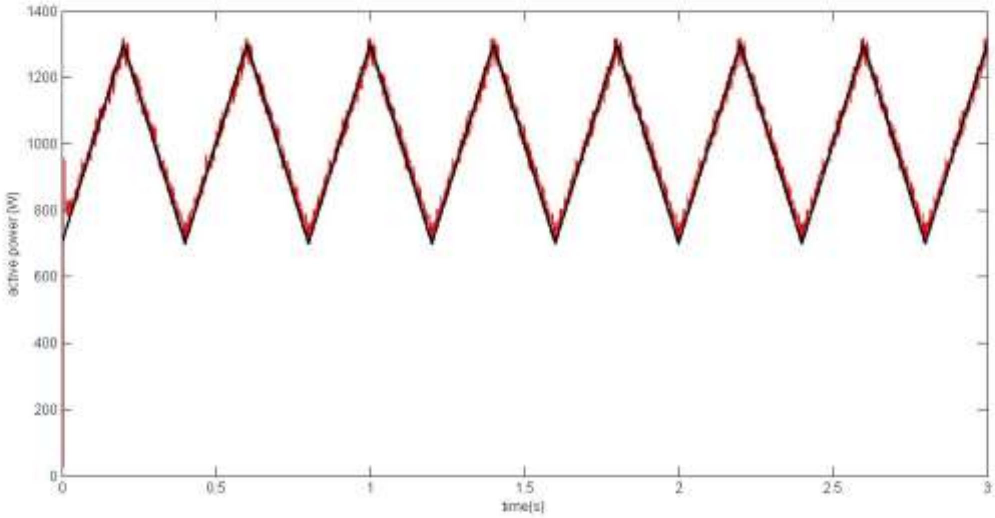

Fig. 10. Tracking of the reference active power dynamic changes by proposed controller system

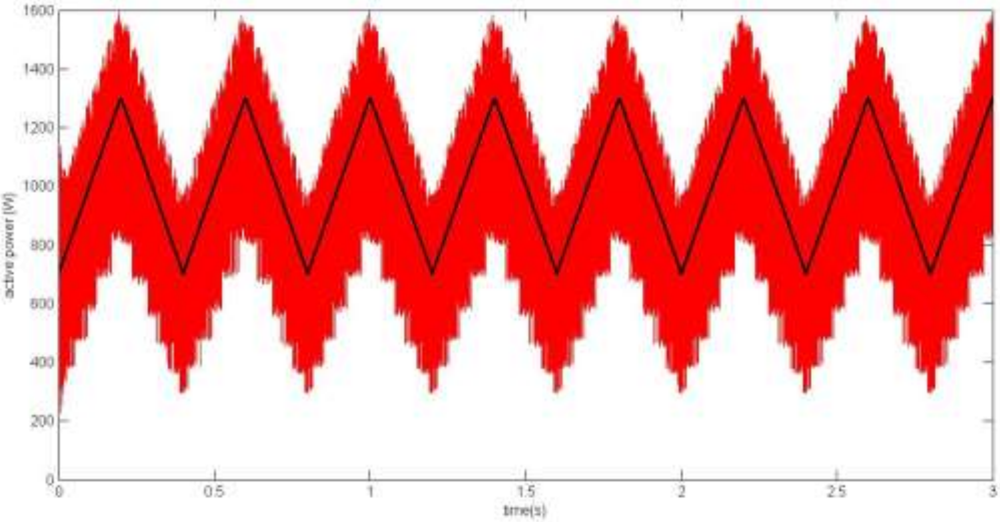

Fig. 11. Tracking of reference active power dynamic changes by conventional PI current controller

5.3. Pulse load Change

In this scenario reference value of active power is considered to be periodic pulses as shown by black color in Fig 10 and 11. Also the measured values of the emulator active power using proposed control strategy and conventional PI controller are plotted respectively in fig 12 and 13 by red color .The comparison of these two figures shows the greater performance of the proposed control system in the rate and accuracy of emulation. Pulse load change can be considered as worst case to evaluate the stability of the system against the sadden reference changes so DC bus current, DC bus voltage and three-phase voltage and current fir this scenario is shown in Fig 14 and Fig 15. As shown in these figures, DC bus voltage is so stable against the pulse changes because of feed-forward control which leads to the stability of three-phase currents. Also DC current change is limited due to the usage of additional LCL filter in DC bus. Unlike PI controller, hysteresis current control is not sensitive to the operation point so it has better response against the sadden pulse changes in reference of the operation point

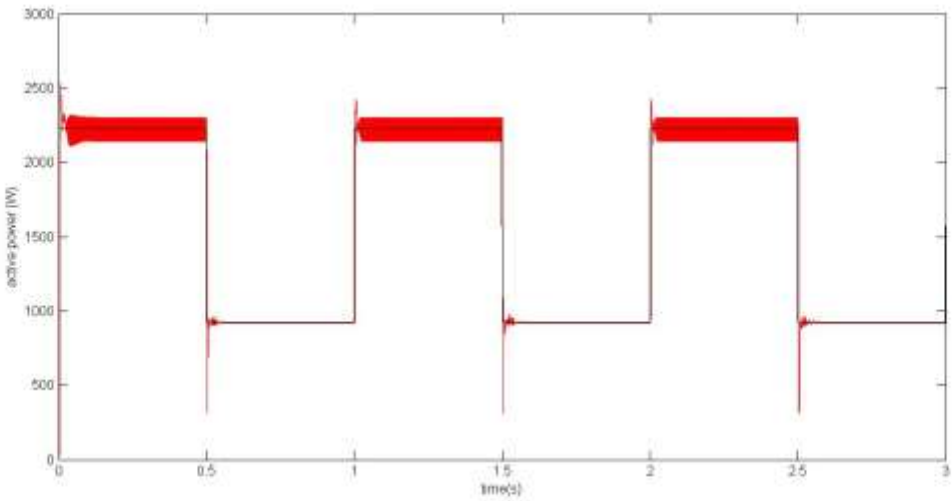

Fig. 12. Tracking of reference active power pulse changes by proposed controller system

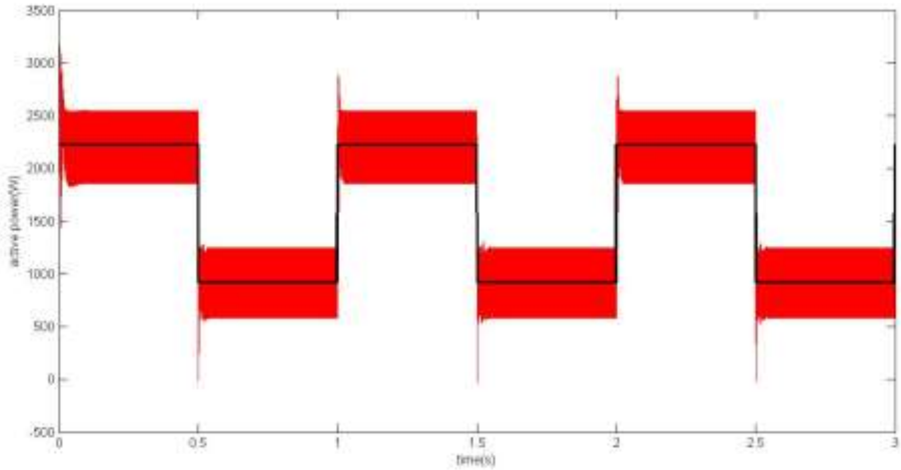

Fig. 13. Tracking of reference active power pulse changes by conventional PI current controller.

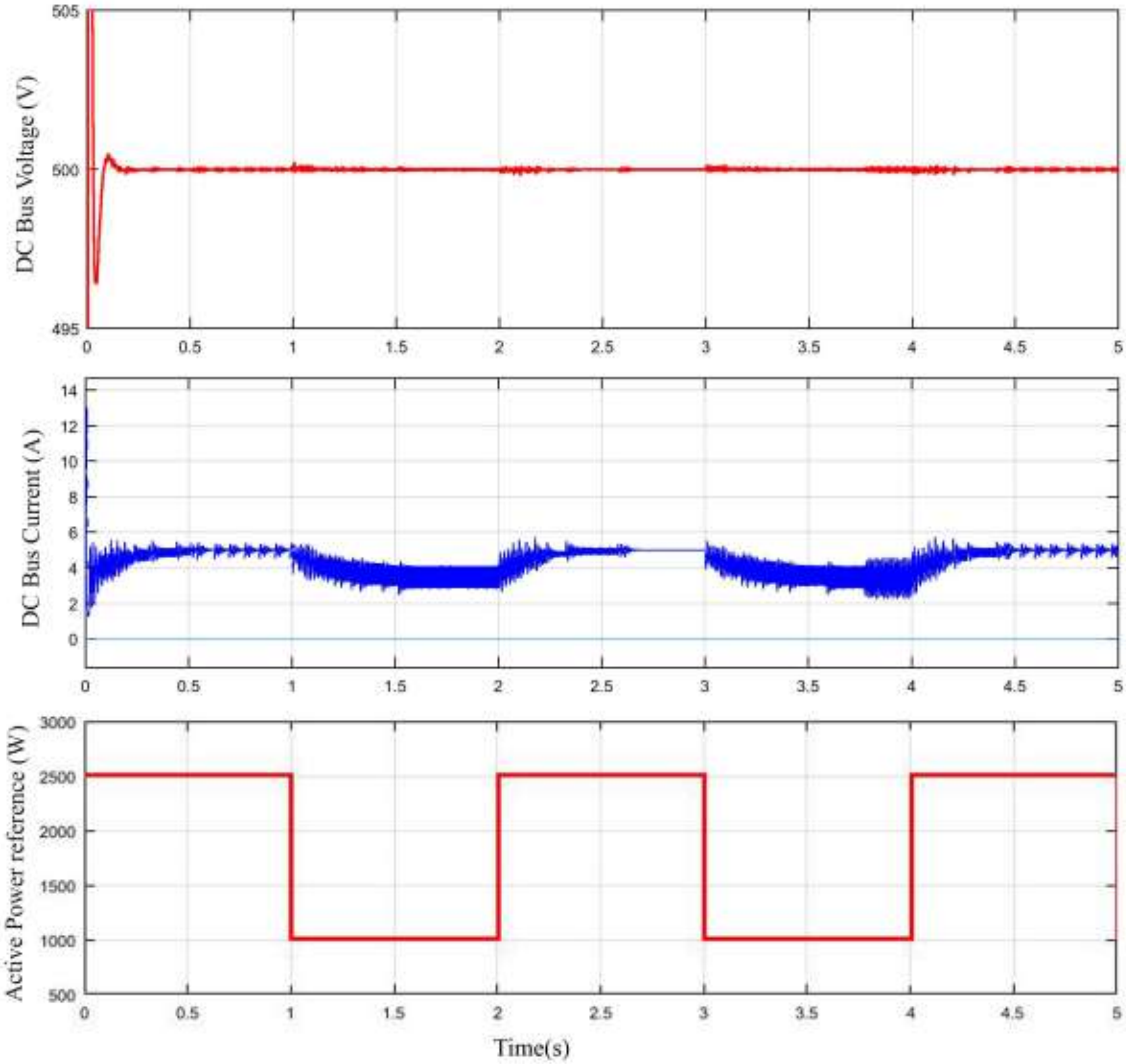

Fig. 14. DC bus voltage and DC bus current over pulse change in active power reference

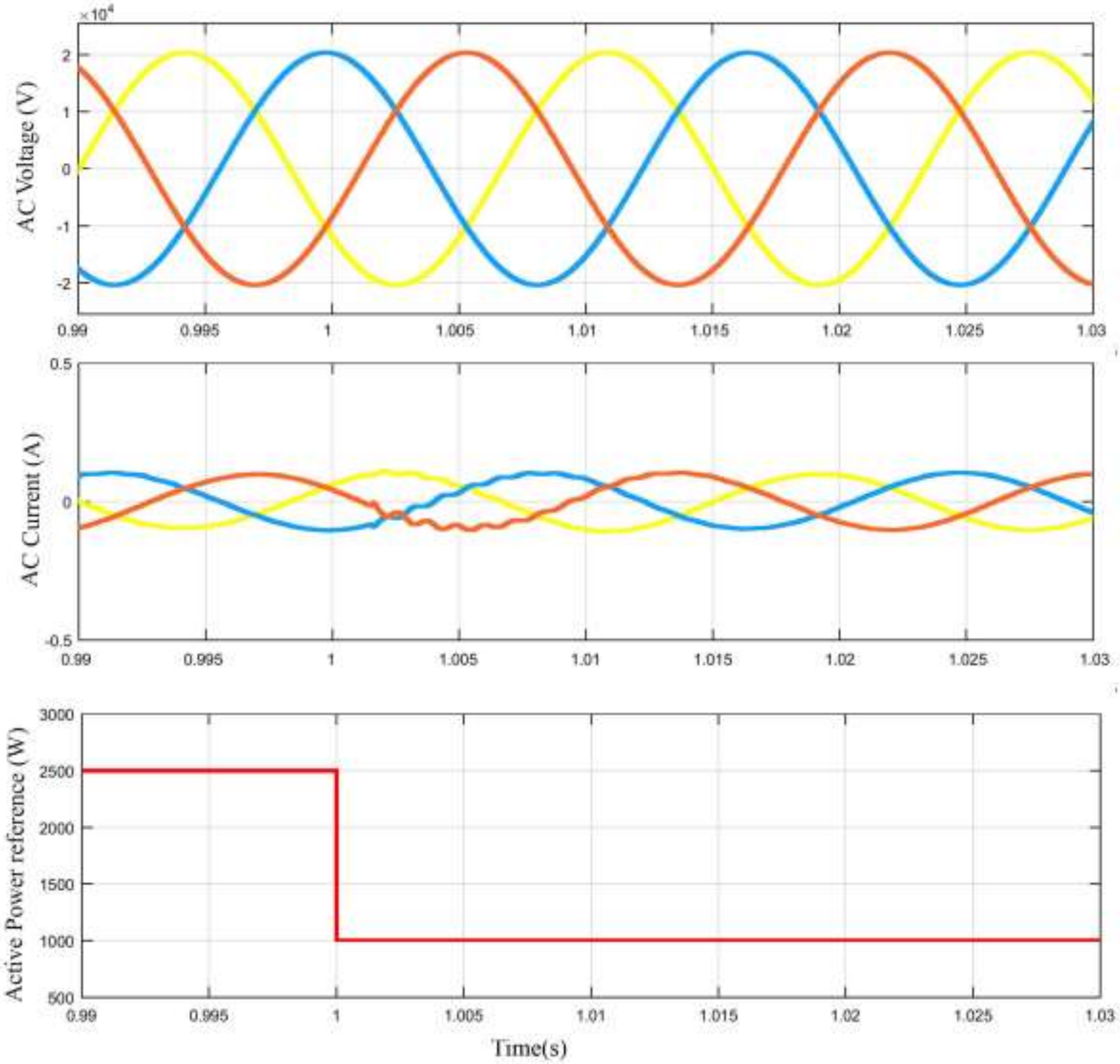

Fig. 15. Three-phase voltage and current over pulse change in active power reference

6. Conclusion

In this paper a modified control system for real time load emulator was presented in which the hysteresis current controller and Feed-Forward current controller has been used. Also optimal addition of a LCL filter to DC link lead to less DC current changes. Simulation results demonstrated the performance of the proposed control system against the conventional PI current controller in three load changes profile including 1) constant reference 2) dynamic change of the reference and 3) pulse change of the reference. The proposed system results in more accurate and faster response in tracking of the reference.

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