A Control Scheme Based on Lyapunov Function for Cascaded H-Bridge Multilevel Active Rectifiers

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***Abstract*— The cascaded H-bridge multilevel active rectifier is a prominent converter configuration. It presents compelling advantages, including high adjustability for a number of applications, such as in solid-state transformers, traction applications, medium and high power motor drives and battery chargers. However, when the H-bridge is operating under an unbalanced load and asymmetrical voltage conditions, it becomes important to design advanced control strategies to maintain the stability of the system. In this study, a Lyapunov-function based control method is proposed for controlling the single-phase cascaded H-bridge active rectifier to achieve global asymptotic stability. A capacitor voltage feedback is added to the conventional Lyapunov-function based stabilizing control method to minimize the resonance of the LCL filter. Additionally, a Proportional-Resonant (PR) control approach is adopted to obtain the reference current signal. This increases the robustness of the current control scheme. A DC voltage balancing control procedure is also employed to prevent the unbalanced DC voltage conditions among the H-bridges. The DC voltage is controlled via a PI controller. The capability of the control approach is verified with simulation and experimental studies.**

Keywords— ***Cascaded H-bridge, current control, LCL filter, Lyapunov function, Proportional-Resonant, voltage balancing.***

I. Introduction

The cascaded H-bridge converter has been seen as the most appealing multilevel topology due to its features, including the ability to be cascaded into multiple single-phase modules, requiring fewer components than its counterparts for the same voltage rating, and being more cost effective [1]-[3]. When it is configured as an AC-DC converter, it provides the advantage of having numerous DC-link voltages for different load ratings. Thus, the cascaded H-bridge topology becomes an enticing solution for solid state transformers, traction applications and medium and high power motor drives [1]-[10].

The cascaded H-bridge rectifier control unit commonly has an output DC voltage control, a utility voltage synchronization unit and a utility current control. In light of the grid current control method, several control schemes have been proposed. The deadbeat current control was introduced in [2] to mitigate the current error at each consecutive sampling period. A module based finite model predictive control was proposed in [9] to minimize computing effort and to enhance the steady-state operation of the current. Cascaded PI regulators were used in [11] to control both voltage and the current of the system. Hysteresis current control methods were introduced and analyzed in [12]-[14] to decrease the current harmonics of the line. The Proportional-Resonant (PR) current control method was demonstrated in [15] for tracking sinusoidal signal and in [16] for monitoring the change in PV irradiation. The predictive current control was introduced in [17] and [18] to reduce switching frequency. A harmonic current elimination PWM control algorithm was presented in [19] for harmonic reduction purposes. Sliding mode control was then proposed in [20] to ensure a consistent DC bus voltage and achieve unity power factor in a cascaded H-bridge boost mode configuration.

In regard to DC-side voltage balancing control algorithm, numerous techniques have been presented in prior art. A PI-based control method was presented in [21] to alleviate the issue of unbalanced voltage of cascaded H-bridge by controlling the power flow of the converter. An indirect controller was used in [22] for ensuring the DC link voltage remained balanced while maintaining the AC current in phase with the utility voltage. In [23], a compensation controller based on three-phase *dq* decoupled strategy was presented to address the unbalanced DC voltage and power of the converter. A unified control algorithm based *dq* frame was analyzed in [24] to balance the cascaded H-bridge DC voltage. In [25], a stable voltage-balancing method using the estimated energy of the DC-link capacitor was used to track the changes in DC voltage of the converter based on adaptive resonant algorithm.

Despite the effectiveness of all the above mentioned controller algorithms, some drawbacks are still present. These include undetermined current spectra, uncertainty under variable switching frequency, sensitivity to the system model accuracy, more involved computational effort and ineffectiveness under extremely distorted input voltage.

This paper presents a Lyapunov-function based current control approach for the cascaded H-bridge active rectifier. The traditional Lyapunov-function technique is customized with an added capacitor voltage feedback. This results in the suppression of the LCL filter resonance. In addition, the inverter side current reference is produced by the PR control method. This both eliminates the dependency of filter component values and the steady state error. By determining the appropriate gain values, the globally asymptotically stability is ensured. Additionally, due to the voltage feedback,

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the transient performance of the system is improved. The proposed control scheme employs a PI controller for the DC voltage control. An additional DC voltage balancing controller, which is introduced in [26], is also employed to prevent unbalanced DC voltage conditions. The simulation and experimental results verify this proposed control system topology and its performance for both transient and steady state conditions.

II. Modeling of The Cascaded H-Bridge Active Rectifier

A. Description

A single-phase cascaded H-bridge rectifier is shown in Fig. 1. The cascaded H-bridge contains three identical cascaded configured single-phase H-bridge modules, which generate the three separated DC bus voltages V_o, V_{o1} and V_{o2}. Each H-bridge consists of four power semiconductor devices connected to a DC bus capacitor C_o, C_{o1} and C_{o2} respectively. Each output capacitor is connected to the resistive load R_o, R_{o1} and R_{o2}, respectively. The input AC source voltage, denoted as V_g, is connected in parallel to the H-bridge input terminals via the LCL filter. The LCL filter is composed of L_f and L_{f1} the filter inductors, R_s and R_{s1} the equivalent resistors of the inductor and C_f the filter capacitor.

III. Proposed Control Scheme

The proposed control scheme is given in Fig. 2. The output DC voltage is controlled by a PI controller. Three output voltages are summed and then divided by three and the average DC voltage value is calculated. This value is considered as a reference voltage value and tracked by the PI based voltage controller. The magnitude of the reference current value is generated by this PI controller. By using the PLL output, the unit reference current signal, which is synchronized with the grid voltage phase and frequency, is generated. Then, the reference current signal which is tracked by the current controller is obtained. A DC voltage balance controller is also employed to remove possible voltage unbalanced conditions.

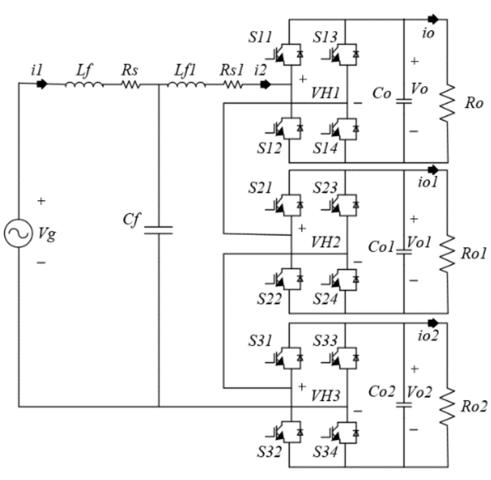

Fig. 1. The topology cascaded H-bridge active rectifier.

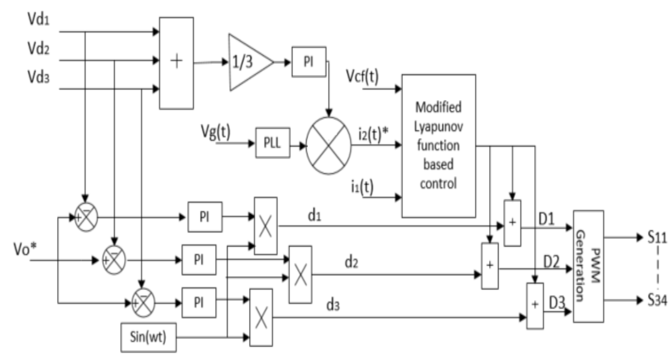

Fig.2 The controller block diagram of the cascaded H-bridge.

A. Lyapunov-Functıon Based Current Control Scheme

The direct technique of Lyapunov stipulates that the state variables are at the stability point when the supplied energy from the power source equals the total energy consumed by the load and active rectifier components.

$$x_1 = i_1 - i_1^* = 0 \tag{1}$$

$$x_2 = i_2 - i_2^* = 0 \tag{2}$$

$$x_3 = v_{C_f} - v_{C_f}^* = 0 \tag{3}$$

Based on this statement, an energy based function $V(x)$ can be written to test the stability of the system [26]-[30]. As stated in the Lyapunov's direct method, the equilibrium point is universally asymptotically stable if $V(x)$ meets: *i*) $V(0)=0$; *ii*) $V(x)>0$ for all $x \neq 0$; *iii*) $V(x) \to \infty$ as $\|x\| \to \infty$; *iv*) $\dot{V}(x)<0$ for all $x \neq 0$. The following Lyapunov equation can be obtained from the stored energy in the inductors and capacitor:

$$V(x) = \Delta E_{L1} + \Delta E_{L2} + \Delta E_C = \frac{1}{2}L_1 x_1^2 + \frac{1}{2}L_2 x_2^2 + \frac{1}{2}C x_3^2 \tag{4}$$

From (4) we can deduce that $V(0)=0$, $V(x)>0$ for all $x \neq 0$ and $V(x) \to \infty$ as $\|x\| \to \infty$. The time derivative of (4) has to be taken to test the last condition and the universal stability of the inverter at its stable point. The time derivative of the Lyapunov-function is given below:

$$\dot{V}(x) = x_1 L_1 \dot{x}_1 + x_2 L_2 \dot{x}_2 + x_3 C_f \dot{x}_3 \tag{5}$$

This equation can be rearranged, as below:

$$\dot{V}(x) = 3V_d x_1 \Delta u - r_1 x_1^2 - r_2 x_2^2 \tag{6}$$

$\dot{V}(x) < 0$ if the disturbed input control is taken as:

$$\Delta u = K_\alpha V_d x_1 \tag{7}$$

where K_α is a real constant and <0. The final equation of the control input can be formulated as:

$$u = U_o + \Delta u = \frac{1}{3V_d}\left(L_1 \frac{di_1^*}{dt} + r_1 i_1^* + v_{C_f}^*\right) + K_\alpha V_d x_1 \tag{8}$$

The $i_2^*(t)$ function in (5) and (6) is generated by multiplying the voltage controller output and unit sine wave. Once the $i_2^*(t)$ is generated, $v_{cf}^*(t)$ and $i_2^*(t)$ can be generated by using (9) and (10), respectively.

$$v_{C_f}^* = L_2 \frac{di_2^*}{dt} + r_2 i_2^* + v_g \tag{9}$$

$$i_1^* = i_C^* + i_2^* = L_2 C_f \frac{d^2 i_2^*}{dt} + r_2 C_f \frac{di_2^*}{dt} + C_f \frac{dv_g}{dt} + i_2^* \tag{10}$$

The control rule given in (8) provides a globally asymptotically stable operation. However, it does not provide the desired damping to minimize the oscillations resulting from the complex conjugate poles of the LCL filter. As a result, the conventional Lyapunov-function based control theory is modified with a capacitor voltage error (x_3) feedback. This new control equation can be stated as:

$$\Delta u = 3K_\alpha V_d x_1 - 3K_\beta x_3 \tag{11}$$

Substituting (11) into (6) gives:

$$\dot{V}(x) = K_\alpha V_d^2 x_1^2 - r_1 x_1^2 - r_2 x_2^2 - K_\beta V_d x_1 x_3 \tag{12}$$

The negative definiteness of $\dot{V}(x)$ is guaranteed if the following inequality is met:

$$K_\beta > \left(K_\alpha V_d - \frac{r_1}{V_d} - \frac{r_2 x_2^2}{V_d x_1^2}\right)\frac{x_1}{x_3} \tag{13}$$

The final control rule including both inverter current and capacitor voltage feedbacks can be formulated as below:

$$u = \frac{1}{3V_d}\left(L_1 \frac{di_1^*}{dt} + r_1 i_1^* + v_{C_f}^*\right) + K_{i1} V_d x_1 - K_d x_3 \tag{14}$$

B. Reference Inverter Current Generation Using PR Controller

The closed-loop control is global asymptotically stable under disturbances away from the operating region with the control law given in (14). i_1^* and v_c^* signals are essential. Although these signals can be calculated by using (9) and (10), generating i_1^* is complicated and requires second order differentiation. Therefore, in this work, a PR control method is utilized to obtain the inverter reference current (i_1^*). Use of a PR controller also removes dependency on the filter component parameters and second order differentiation requirement. It is common knowledge that a PR controller provides a good tracking for AC signals and an infinite gain at ω so that the utility current follows its reference with minimum error in steady-state operation. However, in a practical system, infinite gain is not possible and introduces some problems. Thus, the succeeding non-ideal transfer function equation given below is retained in practice [31]:

$$G_{PR}(s) = K_p + \frac{2K_r \omega_c s}{s^2 + 2\omega_c s + \omega^2} \tag{15}$$

IV. Experimental And Simulation Results

In this study, a single-phase three-cell cascaded H-bridge rectifier is designed, simulated and tested. Simulation studies are carried out with MATLAB/Simulink. The system parameters are given in Table 1. The proposed system is designed to be supplied from 230V grid voltage, and generate 200V DC bus voltage (for each cell).

TABLE I. System Parameters

Symbol	Value
Grid voltage amplitude, V_g	$230\sqrt{2}$ V
Inverter-side inductance, L_1	0.8mH
Filter capacitance, C	$10\mu F$
Grid-side inductance, L_f	0.5mH
Inductor resistors, r_1 and r_2	0.08Ω, 0.05Ω
DC link voltage, V_{dc}	1200V
Grid frequency, f_g	50Hz
Switching frequency, f_{sw}	25kHz

The simulation results are shown in Fig. 3 through Fig. 6. Fig. 3 shows the separated DC bus voltages, the grid current and the grid voltage for steady state. The proposed system draws sinusoidal currents from the grid and generates balanced DC voltage at all three cell outputs.

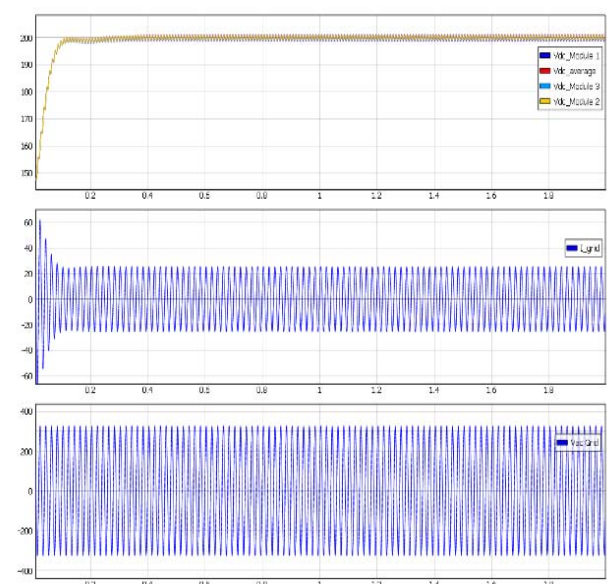

Fig. 3. Simulation results of the average and independent output DC voltage and AC current and voltage waveforms.

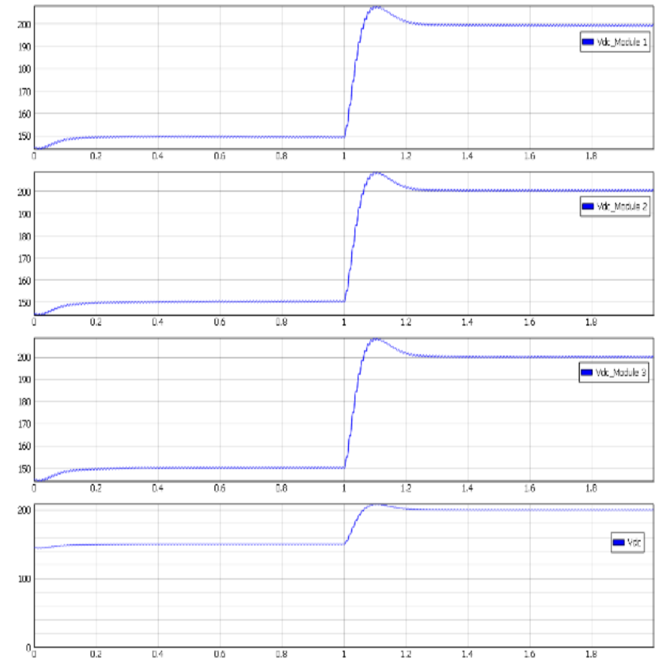

Fig. 4. Simulation results of the average and independent output DC voltage at voltage reference step.

To test the dynamic performance of the system, a step change is applied, and the reference voltage is increased from 150V to 200 at t = 1s. Fig. 4 shows the three separate DC output bus voltages and the average output voltage of the converter when this step change is applied. As seen in the figure, the output voltages are equal and exhibit the same behavior. In Fig. 5, the DC bus voltage of each cell, the grid current and the grid voltage waveforms are given at the step change. As seen from the figures, the proposed system provides fast transient response and sustains the output voltage balance. The proposed system draws sinusoidal current even at transient conditions.

In addition, a step load change is applied to the system. The load level is reduced from 100% to 50% and then increased back to 100% to test DV voltage control, DC voltage balancing control and current control performance. As seen from Fig. 6, all the individual cell output voltages exhibit the same behavior while the system maintains sinusoidal grid current with low harmonic distortions.

Fig.7- Fig.10 show the experimental results. Fig. 7 shows the average DC bus voltage, the grid current and the voltage for $200V$ DC bus voltage reference. Fig. 8 demonstrates all three output DC voltage waveforms (Ch.2, Ch.3 and Ch.4) and the average of these three output voltage waveforms (Ch.1). As seen from the figures, the proposed converter generates balanced cell voltages and draws sinusoidal current from the grid. The harmonics content of the current signal is low and the THD value is measured as 1.7%. Fig. 9 and Fig. 10 demonstrate the dynamic performance of the converter. The load level is both decreased and increased to test the transient response of the proposed controller. It is seen that the proposed control scheme employing the voltage control, the voltage balancing and the Lyapunov-function based current control provide good transient response with very limited overshoot and undershoot. The output voltages also are all well balanced. As seen in the figures below, the proposed control scheme provides high performance for both steady state and transient conditions.

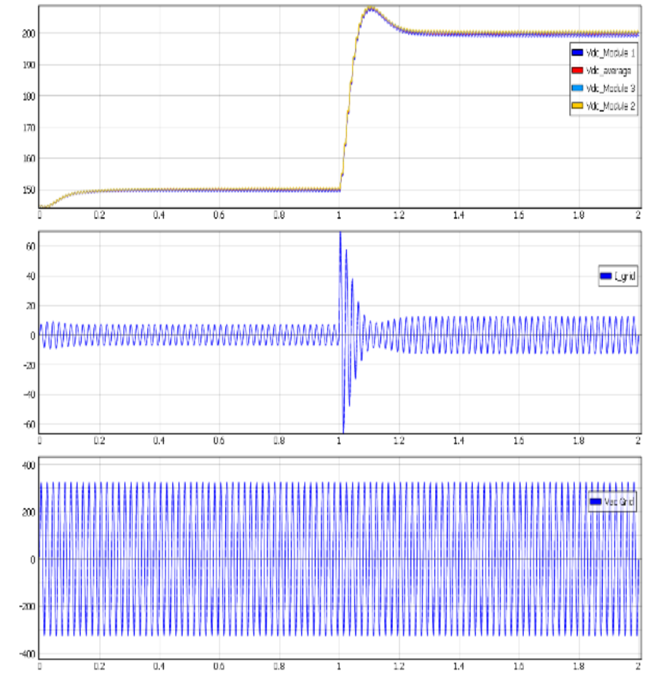

Fig. 5. Simulation results of the average and independent output DC voltage and AC current and voltage waveforms at voltage reference step

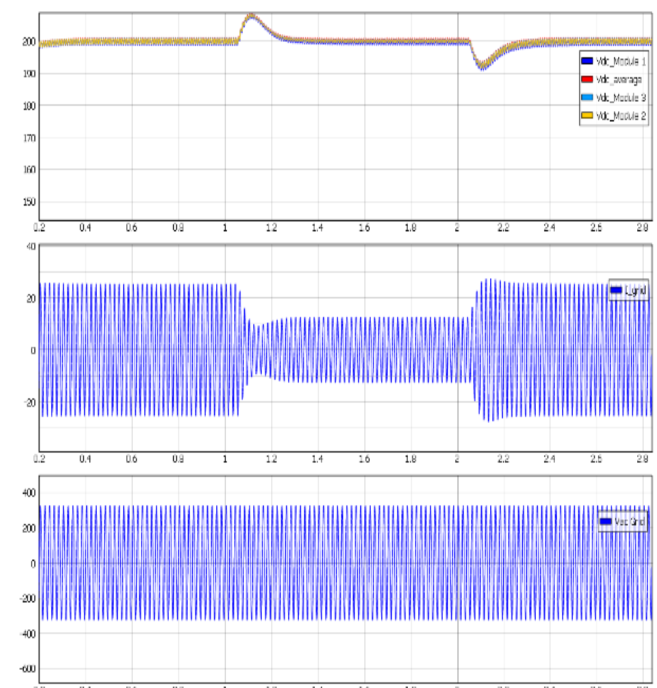

Fig. 6. Simulation results of the average and independent output DC voltage, the grid current and the grid voltage at load step down and step up.

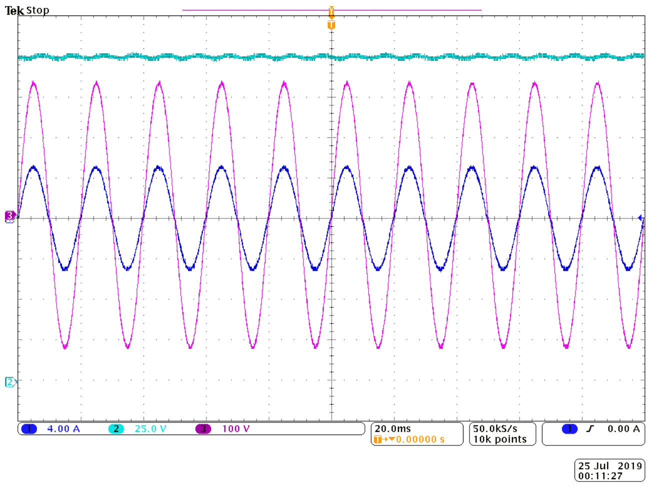

Fig. 7. Experimental results of the grid voltage, DC voltage and grid current waveforms.

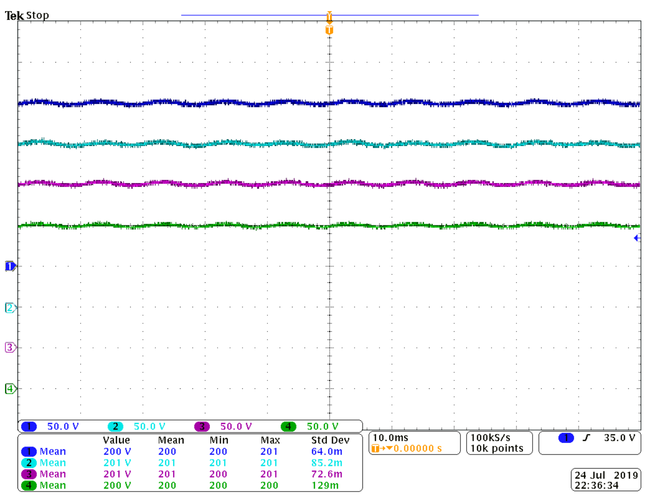

Fig. 8. Experimental results of the average and independent output voltage waveforms.

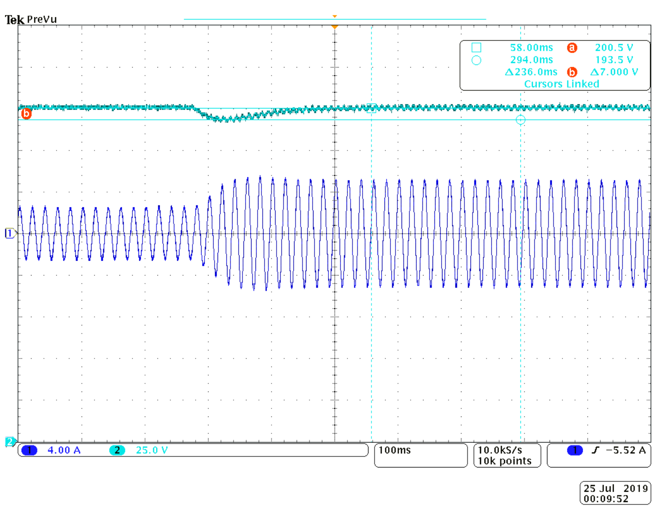

Fig. 9. Experimental results of the grid current and DC voltage waveforms at load step.

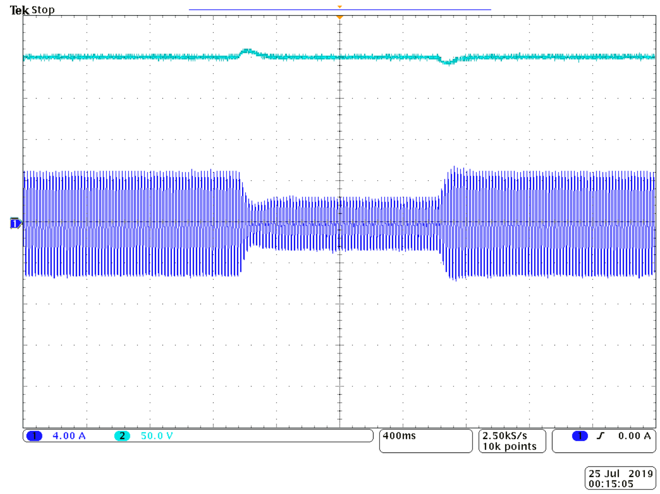

Fig. 10. Experimental results of the grid current and DC voltage waveforms at load step down and step up.

V. CONCLUSION

In this research, Lyapunov based control theory has been utilized to regulate the single-phase three-cell cascaded H-bridge active rectifier with LCL filter. A PI controller has been used for voltage control, which generates the amplitude of the current reference signal. The Lyapunov based control scheme is modified by adding a voltage feedback loop to remove the resonance of the LCL filter. The gain limits of the current control have been provided. The PR controller is designed to generate the inverter current reference signal. This eliminates usage of (7) and improves the robustness of the system. A DC voltage balancing control is also applied to keep the output voltage balanced. The simulation and experimental results prove that the proposed control scheme provides fast transient response and eliminates the steady state error. The rectifier current is in sinusoidal and its THD level is measured as 1.7%.

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