Performance Analysis of Three Level Three Switch Vienna-Type Rectifier based on Direct Power Control

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***Abstract*—The Vienna-type rectifier is broadly employed in various implementations thanks to realizable three-level operation, simple structure and controllable DC-link voltage. This paper proposes an adaptive proportional integral (PI) with anti-windup based direct power control (DPC) to improve dynamic response during load change, DC-link voltage step change and start up and to reduce current tracking errors. An adaptive PI with anti-windup DC-link voltage control is utilized to enhance dynamic response of the DC-link voltage and the instantaneous power because the PI regulator affected by the load change and system parameter variations. The PI based conventional power control is used to indicate the availability and accuracy of the proposed control strategy. The proposed control strategy performs outstanding performance and copes with vigorous disturbances in contrast to the conventional strategy. A detailed theoretical analysis of the proposed approach has been performed. Extensive case studies such as current tracking signals, DC-link voltage step change and load power increase and decrease carried out by PSIM software are performed to validate the excellent behavior of the proposed control strategy.**

Index Terms—**DC-link control; Direct power control; PI with anti-windup; Vienna-type rectifier.**

I. Introduction

VIENNA-TYPE rectifier provides, simple circuit structure, compact size, low voltage stress and achieves a switching voltage that is only half the output voltage. Conventional uncontrolled diode-bridge rectifiers (UDBRs) provide low cost and high reliability. However, the U-DBRs have some limitations uncontrolled power factor, higher total harmonic distortion (THD) and lower efficiency. Therefore, six-switch two levels PWM has been prevailed one of the options owing to the disadvantages of the UDBRs [1]. However, compared to the conventional converters, the Vienna-type rectifiers achieves higher efficiency, less voltage stress, used less power switches, having unity power factor correction, higher reliability and lower cost. It can be utilized in the areas of electric vehicle (EVs) charging, motor drives, uninterruptible power system, hybrid AC/DC energy systems and wind power generation. Besides, the stable and constant DC output voltage is provided for DC/DC power converters in regards to EVs charging [2-6]. The control of the DC-link voltage, power and power factor is considerable important for Vienna-type rectifiers [7].

The operating principle and control of Vienna type rectifiers differ from the traditional rectifiers. The three-level and three switches Vienna-type rectifiers result in unbalance DC capacitor voltages [8]. Voltage and current closed-loop control is commonly utilized for Vienna-type rectifiers. The current control loop is mainly controlled by hysteresis current control (HCC). On the other hand, the proportional integral (PI) control generally has been used by many researchers for the voltage outer loop. However, the slow dynamic response, the linear summation of error and the voltage overrun are some shortcomings [2]. The rectifiers are usually influenced by the external disturbance and changing operation conditions. Various control approaches have been conducted for Vienna-type rectifiers such as HCC method [9, 10], carrier based-discontinuous pulse width modulation (PWM) [11], a lagging reactive power compensation method [12] and a model predictive control (MPC) [13-15]. In these control algorithms, classical PI controller has been employed to regulate the DC-link voltage. However, direct power control (DPC) achieves superior performance for Vienna-type rectifiers compared to the above-mentioned control methods [16]. In [17], authors have presented a DPC based MPC for AC/DC PWM rectifier, but it is affected by variation of the system parameters. On the other hand, sliding mode control (SMC) based control algorithms provision better dynamics and robustness, and also can lessen the overshoots for various disturbance conditions in contrast to the classical PI controller. In [18], Yang et al. have proposed a SMC based control strategy for voltage source rectifier. In [19], Hang et al. have discussed the PI based space vector PWM strategy for Vienna-type rectifier. In [20], authors have addressed deadbeat based MPC for Vienna-type rectifier. Furthermore, to mitigate source current harmonics, a proportional resonant based control approach is discussed for a three-level Vienna rectifier [21].

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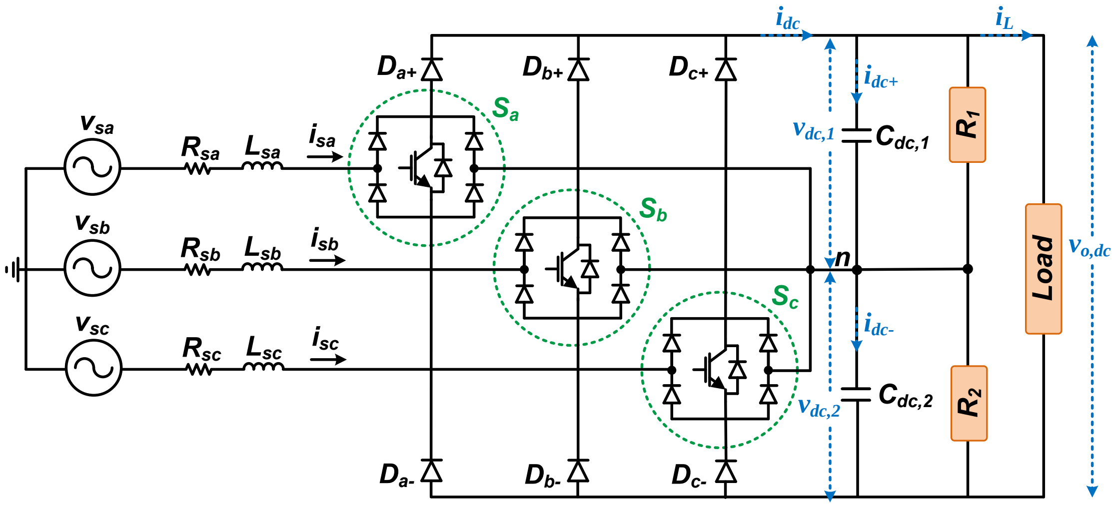

Fig.1 Schematic diagram of the Vienna rectifier topology with dual DC loads.

In [22], He at al. have addressed a hybrid discontinuous PWM for three-level to two-level conversion based Vienna rectifier. A hybrid control scheme including MPC and PI is handled to compensate reactive power and regulate DC-link voltage [23].

This paper proposes a control strategy with a simple and fast dynamic response for three switches three levels Vienna-type rectifier. The DPC has been used in the inner current loop and adaptive PI with anti-windup DC-link control has been adopted in the outer voltage loop, which dealt with slow dynamic response and voltage overshoot in the PI control. Various case results carried out by PSIM software has been conducted to show good robustness and fast tracking performance of the proposed control strategy.

This paper is divided as: The topology of Vienna-type rectifier is discussed in Section II. Section III presents the proposed control strategy. Performance evaluation of the conventional and proposed control strategies are conducted in Section IV. Section V provides main findings of this paper.

II. Description Operational Mode of Vienna-Type Rectifier

The circuit topology of the Vienna-type rectifier represented in Figure 1 includes a three bidirectional switching units (S_a, S_b and S_c) and main diode bridge. The switching units consist of active switches and diode rectifiers, which are controlled to provide steady DC voltage, sinusoidal AC current and neutral point voltage balance [24]. $C_{dc,1}$ and $C_{dc,2}$ divided by two parts as the upper and lower the DC-link capacitors, respectively. The DC-side is tied to the load and the AC-side of the Vienna-type rectifier is tied to the utility grid. $v_{dc,1}$ and $v_{dc,2}$ represent upper and lower the DC-link voltages, respectively.

The operational states of the Vienna rectifier are presented in Figure 2. The polarity of line currents and the ON/OFF states of the switches at any instant of operation have stated the rectifier pole voltages with supposing a continuous conduction mode. With the positive line current (i_{sa}) with the controlled OFF switch S_a, the voltage between the rectifier pole (*A*) and the DC-link neutral point (*n*) is $v_{dc}/2$ as seen in Fig.2a. With the positive line current with the controlled ON switch S_a, the line to neutral voltage v_{an} is 0 (see Fig. 2b). With the negative line current (i_{sa}) with the controlled OFF or ON switch, the line to neutral voltage v_{an} can be $-v_{dc}/2$ or zero. Similarly, this operating procedure can be applied to phases B and C [9] (see Fig. 2c and 2d). Besides, the switching state of Vienna-type rectifier is given in Table I.

The grid current dynamics can be expressed for the AC-side of a Vienna-type rectifier.

$$L_{s,x}\frac{\mathrm{d}i_{s,x}}{\mathrm{d}t}=v_{s,x}-R_{sx}i_{s,x}-\left(v_{n,x}+v_{n0}\right) \tag{1}$$

where *x* represents a-b-c phases. L_s and R_s denote the input inductance and resistance, respectively. It is supposed that $C_{dc,1}=C_{dc,2}=C_{dc}$, and neutral-point voltage is determined with the difference between v_{dc1} and v_{dc2}.

$$\begin{cases} C_{dc,1}\dfrac{\mathrm{d}v_{dc,1}}{\mathrm{d}t}=i_{dc+}-\dfrac{v_{dc,1}+v_{dc,2}}{R_1} \\ C_{dc,2}\dfrac{\mathrm{d}v_{dc,2}}{\mathrm{d}t}=i_{dc-}-\dfrac{v_{dc,1}+v_{dc,2}}{R_2} \end{cases} \tag{2}$$

$v_{x,n}$ is specified by the direction of input AC current and the switching states of bidirectional switches because of the operational characteristics of Vienna-type rectifier [24]. $v_{x,n}$ is written by;

$$v_{x,n}=\left(1-S_x\right)\left(\frac{\mathrm{sign}(i_x)+1}{2}v_{dc,1}+\frac{\mathrm{sign}(i_x)-1}{2}v_{dc,2}\right) \tag{3}$$

where sign(.) defines the sign function.

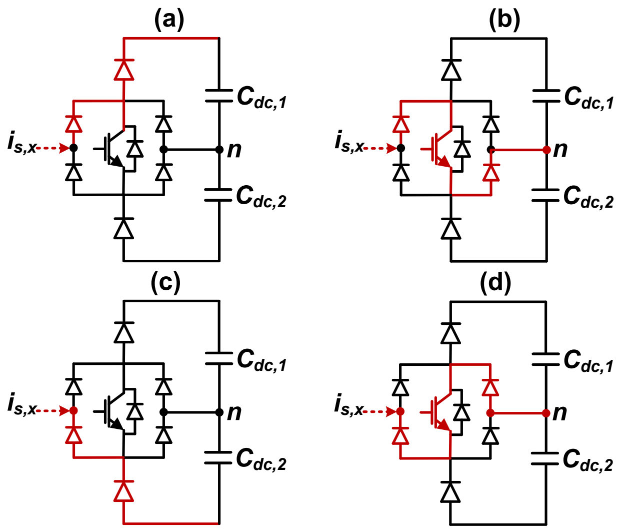

Fig. 2. Current directions for phase units (x = a, b, c); a) positive line current with the controlled OFF switch, b) positive line current with the controlled ON switch, c) negative line current with the controlled OFF switch and d) negative line current with the controlled ON switch.

TABLE I
SWITCHING STATE OF VIENNA-TYPE RECTIFIER

S_a	S_b	S_c	v_{an}	V_{bn}	V_{cn}
0	0	0	$+v_{dc}/2$	$-v_{dc}/2$	$-v_{dc}/2$
0	0	1	$+v_{dc}/2$	$-v_{dc}/2$	0
0	1	0	$+v_{dc}/2$	0	$-v_{dc}/2$
0	1	1	$+v_{dc}/2$	0	0
1	0	0	0	$-v_{dc}/2$	$-v_{dc}/2$
1	0	1	0	$-v_{dc}/2$	0
1	1	0	0	0	$-v_{dc}/2$
1	1	1	0	0	0

III. The Proposed Control Strategy

The proposed control strategy consists of two parts as DC-link voltage and current control loops as depicted in Figure 3. The proposed control strategy has fulfilled the following requirements: providing fast dynamic response under load and DC voltage variations, reducing current tracking errors, low current harmonics and constant switching frequency operation.

A. Adaptive PI with anti-windup DC-link control

Dynamic performances of the DC-link have a considerable significance in the functioning of a rectifier. The dynamic nature of the rectifier is great important for the DC-link regulator to less affect to system parameters, load change and main voltage. In this paper, an adaptive PI with anti-windup control is employed as the DC-link voltage outer loop controller of Vienna-type rectifier to deal with instability and variations of the DC-link voltage. The output of the adaptive PI with anti-windup is used to acquire the active power reference. Output power at the DC-side is equal to the AC-side input power with neglecting power losses [25]. The dynamics of the DC-link voltage is expresses by (4) as;

$$C_{dc}\frac{dv_{dc}}{dt}=i_{dc}-i_L=\frac{P_p^*}{v_{dc}}-i_L \tag{4}$$

where i_L denotes load current. Figure 4 describes the proposed adaptive PI with anti-windup DC-link control and the system dynamics. The control diagram of the DC-link voltage can be designed based on (5). The integral state $\dot{q}$ is written as;

$$\dot{q}=\begin{cases}\Delta v_{dc} & u=u^* \\ \Delta v_{dc}k_i k_{aw}\left(u=u^*\right) & u\neq u^*\end{cases} \tag{5}$$

where $u=u^*$ and $u\neq u^*$ represents linear region and saturation region, respectively. Δv_{dc} is voltage tracking error. Anti-windup gain k_{aw} is commonly chosen as $1/k_p$ [26-31]. Based on Figure 4, the closed-loop function for the DC-link can be obtained as (6);

$$u(s)=\frac{k_p s+k_i}{s-k_{aw}}\Delta v_{dc}-\frac{k_{aw}}{s-k_{aw}}u^* \tag{6}$$

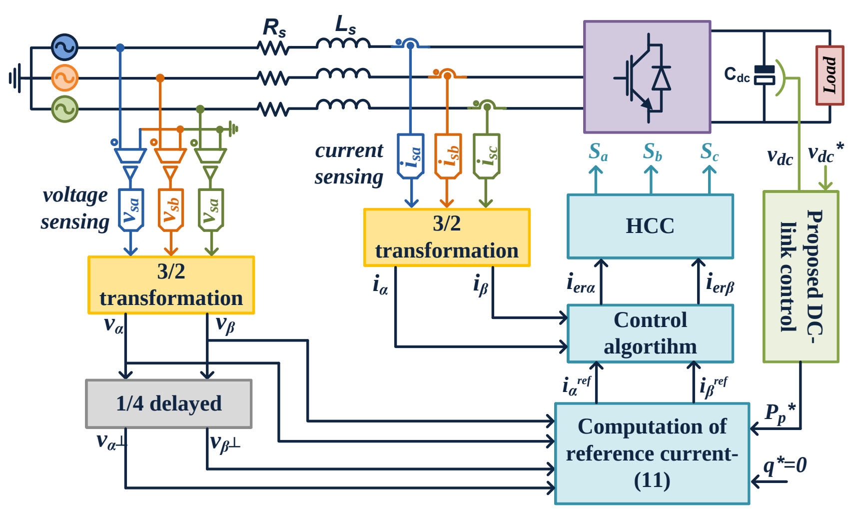

Fig. 3 The entire proposed control strategy.

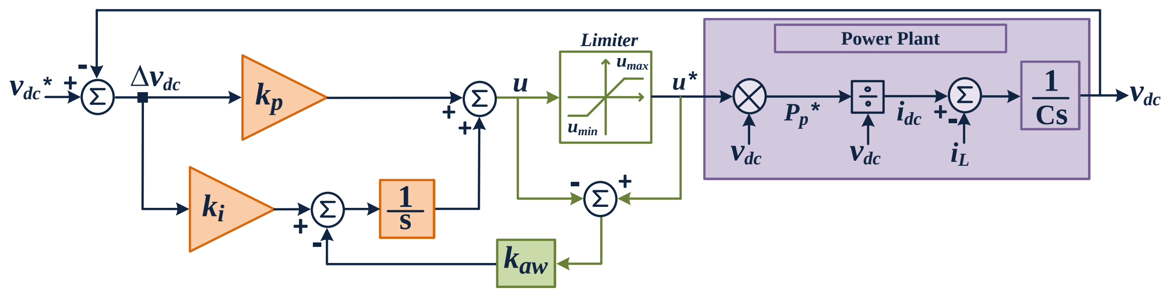

Fig. 4 Adaptive PI with anti-windup control diagram of the DC-link voltage.

B. *Reference current generation*

The control aim for Vienna-type rectifiers is to accurately and quickly track the references of the DC-link voltage and power/current signals. x and $x_{\perp}$ are variable in $\alpha\beta$ stationary coordinate and lagging 90° of x is $x_{\perp}$. Original vector and its delayed value can be utilized to reduce the calculation burden. According to [32-35], $x_{\alpha\beta}^{p}$ and $x_{\alpha\beta}^{n}$ sequences are defined by (7);

$$\begin{pmatrix} x \\ x_{\perp} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ -j & j \end{pmatrix}\begin{pmatrix} x_{\alpha\beta}^{p} \\ x_{\alpha\beta}^{n} \end{pmatrix} \tag{7}$$

The inverse of (7) is given by (8);

$$\begin{pmatrix} x_{\alpha\beta}^{p} \\ x_{\alpha\beta}^{n} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & j \\ 1 & -j \end{pmatrix}\begin{pmatrix} x \\ x_{\perp} \end{pmatrix} \tag{9}$$

The active power reference P_p^* is obtained by the adaptive PI with anti-windup DC-link regulation. Reference reactive power is chosen as zero for both controllers to provide unity power factor. The reference current signals can be obtained by original voltage vectors with their 90° lagging signals.

$$\begin{pmatrix} i_{\alpha}^{*} \\ i_{\beta}^{*} \\ i_{\alpha\perp}^{*} \\ i_{\beta\perp}^{*} \end{pmatrix} = \frac{P_p^*}{\Delta_p}\begin{pmatrix} v_{\beta\perp} \\ -v_{\alpha\perp} \\ -v_{\beta} \\ v_{\alpha} \end{pmatrix} \tag{9}$$

where

$$\Delta_p = v_{\alpha}v_{\beta\perp} - v_{\beta}v_{\alpha\perp} \quad \Delta_p \neq 0 \tag{10}$$

The proposed reference current signals are obtained in αβ-stationary coordinates as;

$$i^{ref} = i_{\alpha} + ji_{\beta} = \frac{P_p^*\left(v_{\beta\perp} - jv_{\alpha\perp}\right)}{v_{\alpha}v_{\beta\perp} - v_{\beta}v_{\alpha\perp}} \tag{11}$$

On the other hand, the conventional reference current signals can be created in αβ-stationary coordinates as [36];

$$i^{ref} = i_{\alpha} + ji_{\beta} = \frac{P_c^*\left(v_{\alpha} + jv_{\beta}\right)}{v_{\alpha}v_{\alpha} + v_{\beta}v_{\beta}} \tag{12}$$

where P_c^* is created based on the conventional PI control.

IV. Results and Discussions

Performance Analysis of Three Switches Three Levels Vienna-Type Rectifier has been simulated in PSIM software environment to demonstrate the effectiveness of the proposed control strategy. The parameters for the proposed system are given in Table II. Two control strategies are applied in Vienna-type rectifier system to achieve validity of the proposed control strategy. Switching signals for two control strategies are created based on the HCC.

- One strategy is conventional control that includes conventional PI DC-link control and conventional reference current generation.
- Another strategy is proposed control that includes adaptive PI with anti-windup DC-link control and DPC.

TABLE II
SIMULATION PARAMETERS

Parameters	Values
Source line voltage v_a, v_b, v_c (rms)	220V
Source frequency	50Hz
DC-link capacitance	$C_{dc,1}$=$C_{dc,1}$=1000uF
Load	5Ω/15Ω
Filter inductance	1mH

The steady-state, dynamic response and current tracking errors waveforms of the conventional and proposed control strategies are depicted in Figure 5. It is indicated that the proposed control strategy can accomplish good tracking of current references with nearly 8ms while the conventional control has slower dynamic response with about 30ms (see Figure 5a and 5b). Besides, current tracking errors are effectively minimized by the proposed control.

Figure 6 depicts the comparison of the results between conventional and the proposed control under increasing dynamic load power (sudden change of R_L value from 10 to 6.67Ω). While the DC-link voltage is restored with the proposed control to the given value within nearly 10ms, the conventional control has slower dynamic response with about 50ms to provide to the given value.

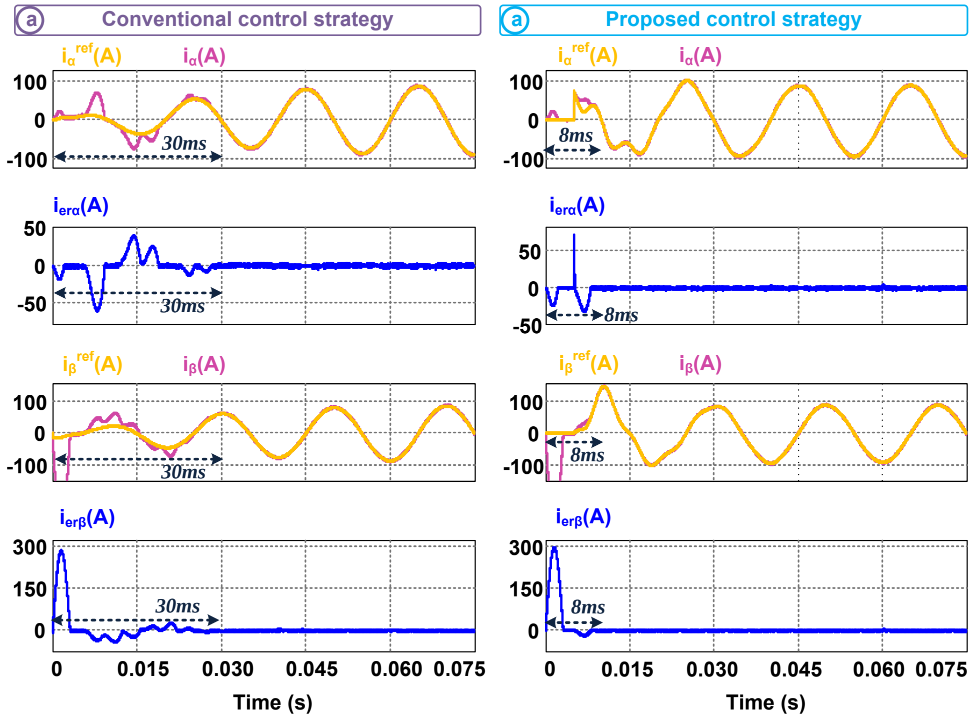

Fig. 5 Current tracking signals for a) conventional control and b) proposed control

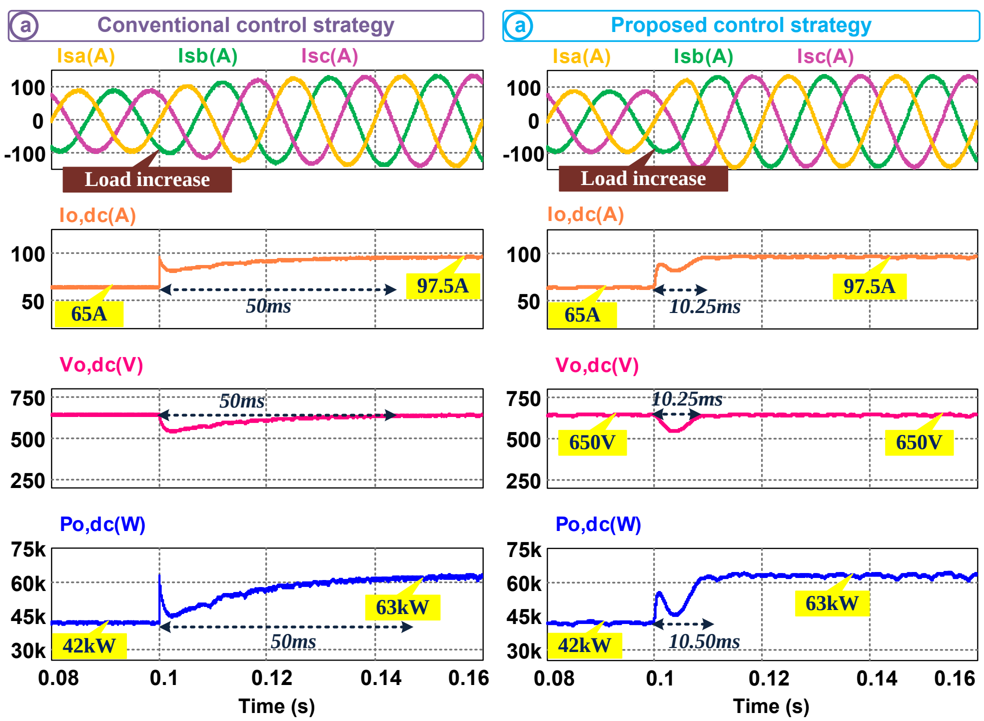

Fig. 6 Load power increase for a) conventional control and b) proposed control

The effectiveness of the proposed control strategy is also examined under load power decrease (sudden change of R_L value from 10 to 15Ω) as depicted in Figure 7. With the proposed control, the output current, DC-link voltage and output power soon achieve a steady state within 25ms while with the conventional control, these signals has been reached a steady state within 45ms. The results indicate that the proposed control provisions strong robustness against sudden load disturbances in contrast to the conventional control.

Figure 8 reveals the control of the DC link voltage ($V_{o,dc}$) is achieved at 650V, 700V and 625V after the step change occurs in reference DC-link voltage (V_{dc}^*). The fast regulation of the DC-link voltage is effectively accomplished with 25ms for the proposed control under this operation while the dynamic response with the conventional control is slower with 45ms as shown in Figure 8a. While the current THD of the conventional control is 1.7%, the current THD is only 0.9% with using the proposed control.

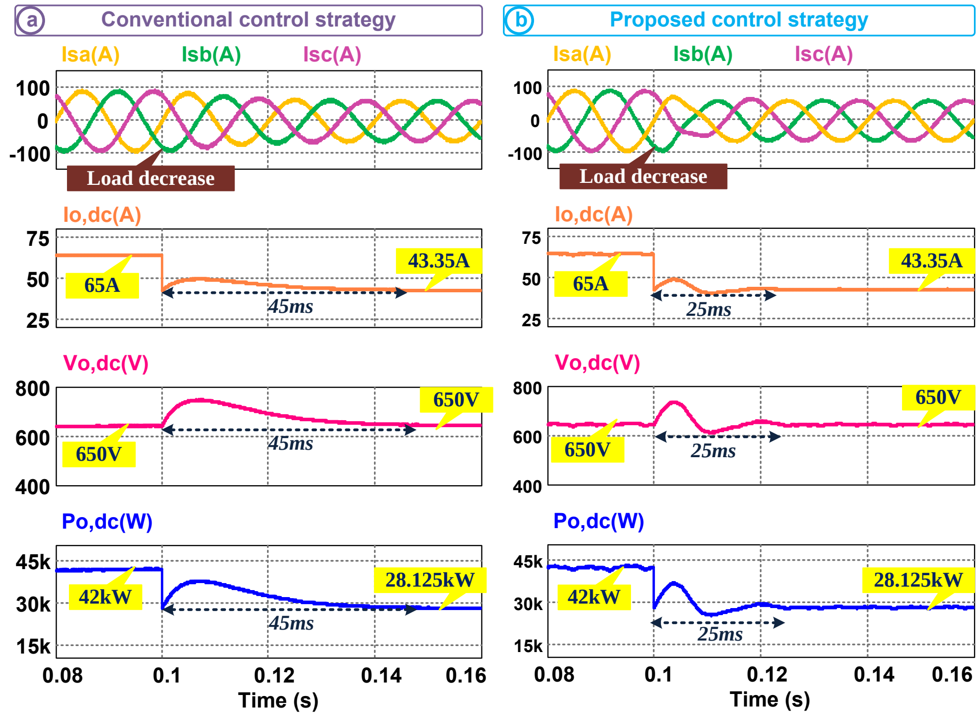

Fig. 7 Load power decrease for a) conventional control and b) proposed control

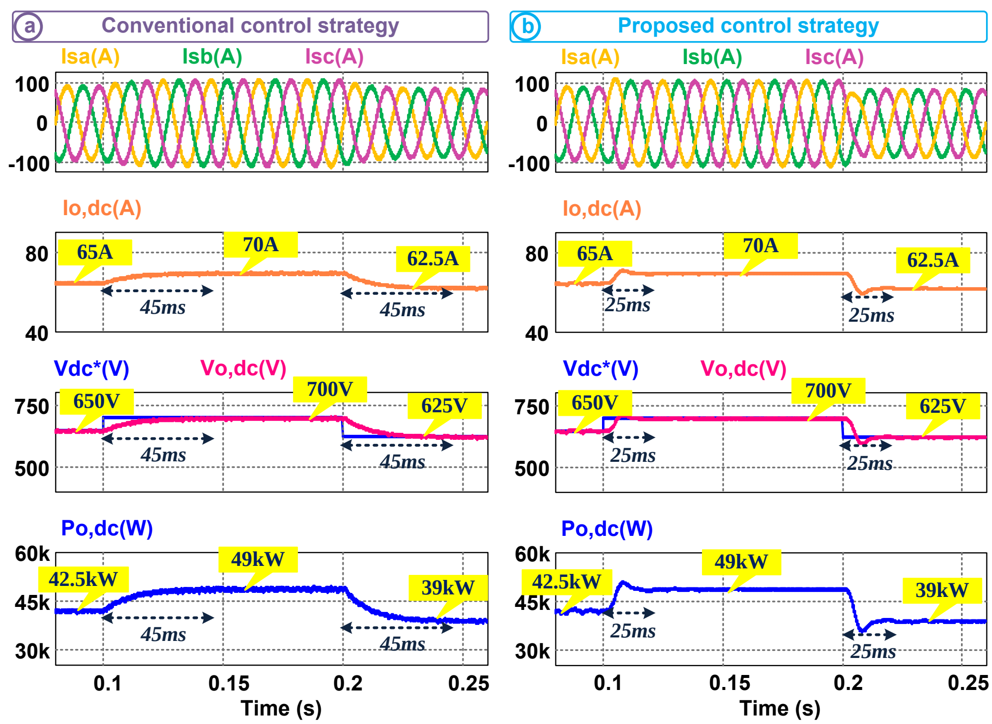

Fig. 8. DC-link voltage step change for a) conventional control and b) proposed control

V. CONCLUSION

In this paper, to achieve fast dynamic response and low current tracking errors, adaptive PI with anti-windup based DPC is proposed. The DPC is employed to generate current signals and adaptive PI with anti-windup control is utilized to acquire the desired DC-link voltage. The above analysis and results have indicated that the proposed control enhances the fast response speed and reduces current tracking errors. The proposed control can accomplish better tracking of current references and the DC-link voltage step change within nearly 8ms and 25ms, respectively although the conventional control strategy provides 30ms and 45ms for them. Besides, the DC-link voltage has been kept under all cases. The proposed control achieves good robustness against sudden load disturbances compared to the conventional control. The proposed control strategy has carried out the operation of Vienna-type rectifier under various case studies, effectively.

However, although adaptive PI with anti-windup have a broad range of gain alteration; the error can occur with large gain.

The proposed control can be employed in various applications such as wind power generation systems, the charging station of an EV and boost-type unidirectional converter topologies. Besides, the future scope of this study is to improve a control strategy for fast charging EVs.

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