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Proportional-Integral and Proportional-Resonant Based Control Strategy for PUC Inverters

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Abstract—In this paper, a proportional-integral (PI) and proportional-resonant (PR) based control strategy is proposed for packed-U-cell (PUC) inverters. In the conventional PI-PI based control strategy, while the first PI regulates the DC capacitor voltage, the second PI regulates the AC load current. However, it is shown that the second PI cannot guarantee zero tracking error in the load current. The main reason of this comes from the fact that PI controllers are not able to achieve zero tracking error for the AC signals. Also, in an attempt to reduce the tracking error by tuning PI gains distorts the load current. In this study, a PI-PR based control strategy is obtained by replacing the second PI by a PR controller. The performances of both PI-PI and PI-PR control methods have been compared. It is shown that the load current to tracks its reference in all circumstances provided that the inverter current reference is generated accurately. Computer simulations are conducted to show the steady-state and dynamic performances of both control methods.

Keywords—Packed-U-cell (PUC) inverter, proportional-integral control (PI), proportional-resonant (PR) control.

I. INTRODUCTION

Power converters such as uninterruptible power supplies, off-grid inverters and on-grid inverters have come a long way through developmental stages and made their applications almost inevitable due to the need of power efficiency and performance requirements. The traditional converters like the full-bridge or half-bridge topologies are the most preferred low-cost power structures for the industry. When traditional converters are used to inject the energy from a dc source to ac grid, the harmonic components should be considered at the filter side especially at the high-power applications. In order to reduce voltage stresses and distortions, multilevel converters like neutral point clamped (NPC) [1], [2] and flying capacitor (FC) [3], [4] converters are proposed. The main advantage of multilevel converters is that they generate voltage and current waveforms with low harmonic distortion. However, their implementation is complicated and costly due to the high number of switches, capacitors and diodes employed in a typical n-level converter.

Packed-U-Cell (PUC) converter is proposed as an alternative to the NPC and FC converters [5]. Detailed comparison of the PUC converter with the well-known topologies is presented in [6]. The 7-level PUC converter topology has six switches and two dc-links. For inverter applications, a battery source should be connected to the first

dc-link and a capacitor is used for the second dc-link. In this topology, the PUC inverter operates successfully if the dc capacitor voltage is controlled. In" recent literature, increasing attention has been paid to the PUC converters due to the various advantages over the traditional dc-ac converters. However, the PUC based drivers or inverters are not yet ready for mass production. This is mainly because of the difficulties in the dc-link capacitor voltage control and switching issue.

To solve the above-mentioned limitations of the PUC based converter topologies various methods have been investigated in the last ten years. When the PUC is operated as an inverter, the objectives of the control strategies include the regulation of dc capacitor voltage and load current. Various control strategies such as hysteresis control [6], voltage balancing control [7], cascaded nonlinear control [8], finite-control-set model predictive control [9], model predictive control [10], [11], multi-objective model predictive control [12] and sensor-less based control [13] are proposed to achieve these objectives. In these works, the control approach is based on using two proportional-integral (PI) controllers. While the first PI is used to control the capacitor voltage, the second one is used to control the load current. The first PI controller generates the amplitude of the reference load current by processing the capacitor voltage error. On the other hand, the second PI controller produces the sinusoidal modulating signal by processing the load current error. The main drawback of these methods is the inability of the second PI in achieving zero tracking error in the load current. Also, in an attempt to reduce the tracking error by tuning PI gains distorts the load current.

In this paper, a PI-proportional resonant (PI-PR) based control strategy is proposed for PUC inverters. It is well known that PR controllers exhibit excellent performance in tracking an AC reference signal. Motivated from this fact, the conventional PI-PI based control is modified by replacing the second PI with a PR controller. The performances of both PI-PI and PI-PR control methods have been compared. The main advantage of the proposed PI-PR based control strategy is that the load current tracks its reference in all circumstances provided that the inverter current reference is generated accurately. Computer simulations are conducted to show the steady-state and dynamic performances of both control methods.

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II. SEVEN-LEVEL PUC INVERTER MODELING

The single-phase 7-level PUC inverter containing six switches, one isolated dc source and one capacitor is shown in Fig. 1. Each cell is constituted by the pair of $(Q_i, \bar{Q}_i)$ and a capacitor. The operation of the switches is defined as

$$Q_i = \begin{cases} 0, & \text{if} \quad Q_i \text{ is OFF} \\ 1, & \text{if} \quad Q_i \text{ is ON} \end{cases} \quad , \quad i = 1, 2, 3 \quad (1)$$

It should be noted that Q_i and $\bar{Q}_i$ work complementarily. This means that each pair of $(Q_i, \bar{Q}_i)$ cannot conduct simultaneously. Since each cell has two switches, the PUC inverter with three cells can produce an output voltage with seven levels. The switch states and output voltage levels are depicted in Table I.
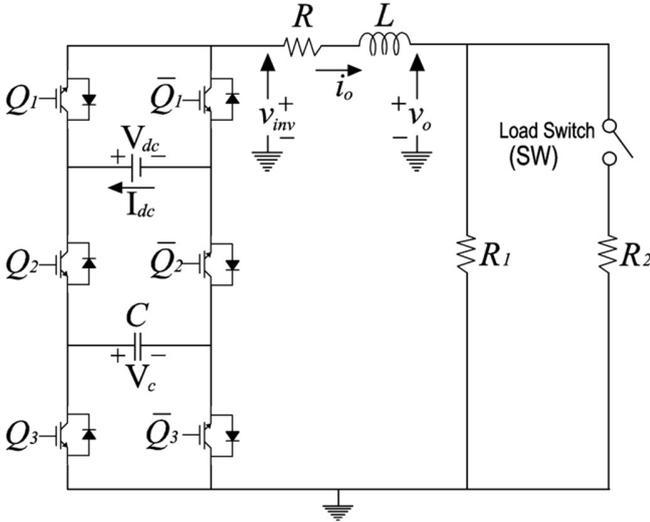

Fig. 1. Seven-level single-phase PUC inverter.

TABLE I
SWITCHING STATES AND SEVEN LEVELS GENERATED BY PUC INVERTER

$(Q_1, \bar{Q}_1)$	$(Q_2, \bar{Q}_2)$	$(Q_3, \bar{Q}_3)$	v_{inv}
1, 0	0, 1	0, 1	V_{dc}
1, 0	0, 1	1, 0	$V_{dc}-V_c$
1, 0	1, 0	0, 1	V_c
1, 0	1, 0	1, 0	0
0, 1	0, 1	0, 1	0
0, 1	0, 1	1, 0	$-V_c$
0, 1	1, 0	0, 1	V_c-V_{dc}
0, 1	1, 0	1, 0	$-V_{dc}$

In order to obtain seven output voltage levels, it is required to have $V_{dc} = 3V_c$. In Table I, replacing V_{dc} by $V_{dc} = 3V_c$ results in 0, $\pm V_c$, $\pm 2V_c$ and $\pm 3V_c$. In order to obtain these levels, the capacitor voltage (V_c) should be regulated at $V_{dc}/3$. Clearly, two of the states generate zero voltage at the inverter output. On the other hand, it is obvious that the maximum value of inverter output voltage (v_{inv}) cannot exceed the dc source voltage (V_{dc}). The differential equations describing the operation of the inverter can be written as

$$C\frac{dV_c}{dt} = (Q_3 - Q_2)i_o \quad (2)$$

$$L\frac{di_o}{dt} + Ri_o = v_{inv} - v_o \quad (3)$$

where $v_{inv} = (Q_1 - Q_2)V_{dc} + (Q_2 - Q_3)V_c$.

III. CONVENTIONAL PI-PI BASED CONTROL STRATEGY

The objectives of the control strategies devised for PUC inverter include the regulation of dc capacitor voltage (V_c) and load current (i_o). Various control strategies such as hysteresis control [6], voltage balancing control [7], cascaded nonlinear control [8], and finite-control-set model predictive control [9] are proposed to achieve these objectives. In these control methods, the capacitor voltage is regulated by using a proportional-integral (PI) controller which processes the capacitor voltage error and produces the amplitude of the reference load current as follows

$$I_o^* = K_{p1}(V_c^* - V_c) + K_{i1}\int(V_c^* - V_c)dt \quad (4)$$

where I_o^* denotes the amplitude of reference load current i_o^*. In the steady-state, I_o^* converges to a value which can be computed from power balance equation as follows

$$I_o^* = \frac{2I_{dc}V_{dc}}{V_o} \quad (5)$$

In (5), V_o denotes the amplitude of v_o. The reference load current can be obtained by multiplying I_o^* with the unit sine wave as follows

$$i_o^* = I_o^* \sin \omega t \quad (6)$$

In order to regulate the load current i_o, a second PI controller is used to produce the sinusoidal modulating signal as follows

$$m = K_{p2}(i_o^* - i_o) + K_{i2}\int(i_o^* - i_o)dt \quad (7)$$

The modulating signal is compared with the level shifted triangular waveforms to produce the pulse width modulation (PWM) signals shown in Table I. The block diagram of this control method is shown in Fig. 2.
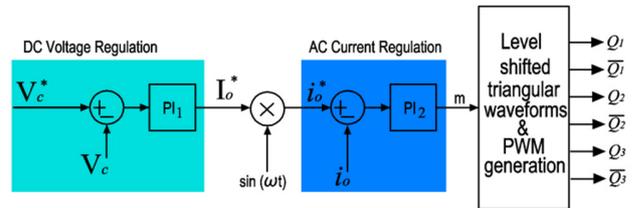

Fig. 2. Block diagram of conventional control method using two PI controllers.

It is well known that PI controllers exhibit good dynamic and steady-state performance for dc quantities. However, their

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performance in the regulation of sinusoidal quantities, such as load current i_o, is not satisfactory.

IV. PI-PR BASED CONTROL STRATEGY

Due to the excellent performance in tracking an AC reference signal, the proportional-resonant (PR) controllers are widely used in the regulation of AC variables. In this study, the modulation signal shown in (7) is proposed to be generated by a proportional-resonant (PR) controller whose transfer function is given by

$$G(s) = K_{pr} + \frac{2K_r \omega_c s}{s^2 + 2\omega_c s + \omega^2} \qquad (8)$$

where ω_c is the cut-off frequency, ω is the resonant frequency, K_{pr} and K_r are proportional and resonant gains, respectively. The operation of PR controller can be described by the internal model principle proposed in [14]. The input applied to the PR controller is the load current error $(i_o^* - i_o)$. According to this principle, if ω is set to the frequency of reference load current, which is 100π rad/s in this study, the PR controller generates a sharp peak at $\omega = 100\pi$ rad/s resulting in zero steady-state error in $(i_o^* - i_o)$. In other words, one can say that i_o tracks its reference i_o^* without any error. It is worth noting that $G(s)$ in (8) represents a non-ideal transfer function used in practical applications. The ideal transfer function which does not involve ω_c and $2\omega_c s$ terms in the nominator and denominator, respectively, cannot be realized in practice. The magnitude and phase responses of ideal and non-ideal PR are shown in Fig. 3. It is evident that the gain of magnitude response at $\omega = 100\pi$ rad/s obtained by non-ideal PR has been reduced considerably. The desired dynamic and steady-state responses of the inverter can be obtained by tuning K_{pr} and K_r.
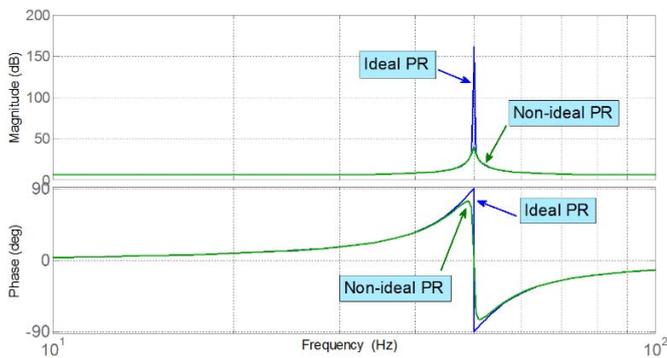

Fig. 3. Magnitude and phase responses of ideal and non-ideal PR.

V. SIMULATION RESULTS

The effectiveness and correct operation of the proposed control strategy has been verified by simulations using Matlab/Simulink. The system and control parameters used in the simulation studies are given in Table II.

TABLE II
SYSTEM AND CONTROL PARAMETERS

Description and Symbol	Value
DC source voltage, V_{dc}	150V
Capacitance, C	2000µF
Filter inductance, L	5mH
Resistance of inductor, R	0.5Ω
Load resistance, R_1 and R_2	10Ω , 10Ω
Switching frequency, f_s	8kHz
Sampling time, T_s	30µs
Reference capacitor voltage, V_c^*	30V
Gains of first PI, K_{p1} and K_{i1}	0.25 , 10
Gains of second PI, K_{p2} and K_{i2}	1.5 , 50
Gains of PR, K_{pr} and K_r	1.79 , 700
Cut-off frequency, ω_c	1 rad/s

The block diagram of seven-level single-phase PUC inverter with the proposed PI-PR based control strategy is shown in Fig. 4.
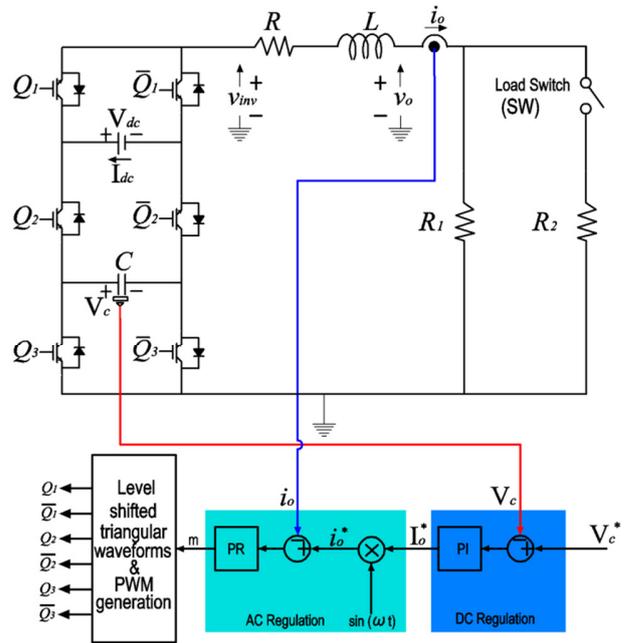

Fig. 4. Block diagram of seven-level single-phase PUC inverter with the proposed PI-PR based control.

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Fig. 5 shows the steady-state responses of i_o, i_o^* and m obtained by the conventional PI-PI based control strategy under R_1. It can be seen from Fig. 5(a) that i_o cannot track i_o^* with zero steady-state error. The main reason of this comes from the insufficient performance of the second PI controller in regulating the AC load current. Also, the total harmonic distortion (THD) of i_o is computed to be 3.96%. The modulating signal (m) is shown in Fig. 5(b).
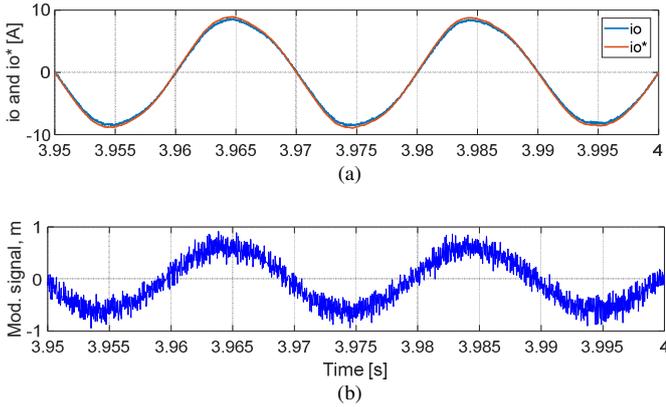
Fig. 5. Steady-state responses of i_o, i_o^* and m obtained by the conventional PI-PI based control under R_1. (a) i_o and i_o^* (b) m.

Fig. 6 shows the dynamic responses of AC and DC variables obtained by the conventional PI-PI based control strategy when R_2 is disconnected suddenly at t=2s. It is obvious from Fig. 6(a) that i_o tracks its reference whose amplitude is generated by the first PI controller. It can be seen from Fig. 6(b) that the capacitor voltage tracks its reference successfully. The inverter output voltage has seven levels (-150V, -100V, -50V, 0V, +50V, +100V, and +150V) as shown in Fig. 6(c).

Fig. 7 shows the steady-state responses of i_o, i_o^* and m obtained by the proposed PI-PR based control strategy under R_1. It can be seen from Fig. 7(a) that i_o tracks i_o^* with zero steady-state error. The THD of i_o is computed to be 2.98%. The modulating signal (m) is shown in Fig. 7(b).
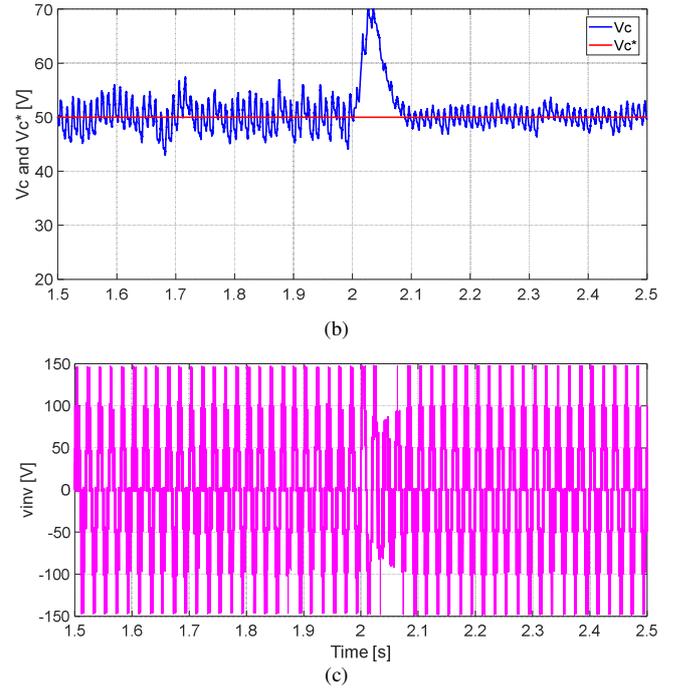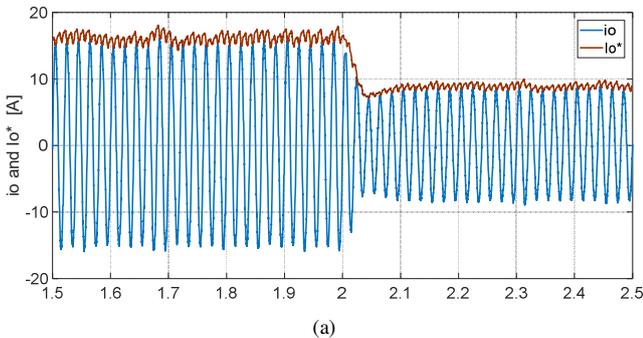
Fig. 6. Dynamic responses of AC and DC variables obtained by the conventional PI-PI based control when R_2 is disconnected suddenly at t=2s. (a) i_o and I_o^* (b) V_c and V_c^*, (c) v_{inv}.

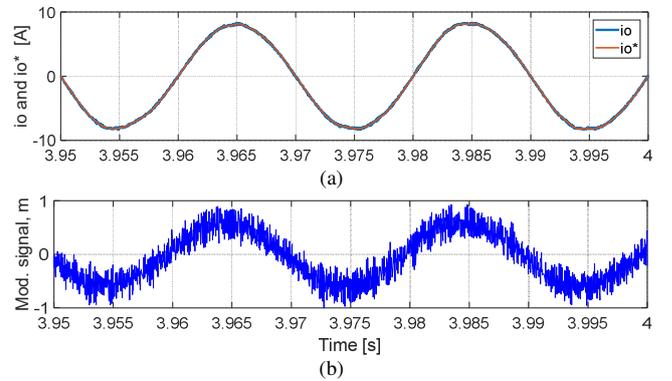Fig. 7. Steady-state responses of i_o, i_o^* and m obtained by the proposed PI-PR based control under R_1: (a) i_o and i_o^* (b) m.

Comparing Figs. 5 and 7, one can see that the proposed PI-PR based control strategy performs better than the conventional PI-PI based control strategy in terms of load current's THD and tracking capability.

Fig. 8 shows the dynamic responses of AC and DC variables obtained by the proposed PI-PR based control strategy when R_2 is disconnected suddenly at t=2s. It is obvious from Fig. 8(a) that i_o tracks its reference whose amplitude is generated by the first PI controller. The capacitor

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voltage tracks its reference successfully as clearly shown in Fig. 8(b). The inverter output voltage (v_{inv}) displayed in Fig. 8(c) has seven levels as mentioned in the Introduction. Comparing, Figs. 6 and 8, one can see that the dynamic performances of both methods are very close to each other.
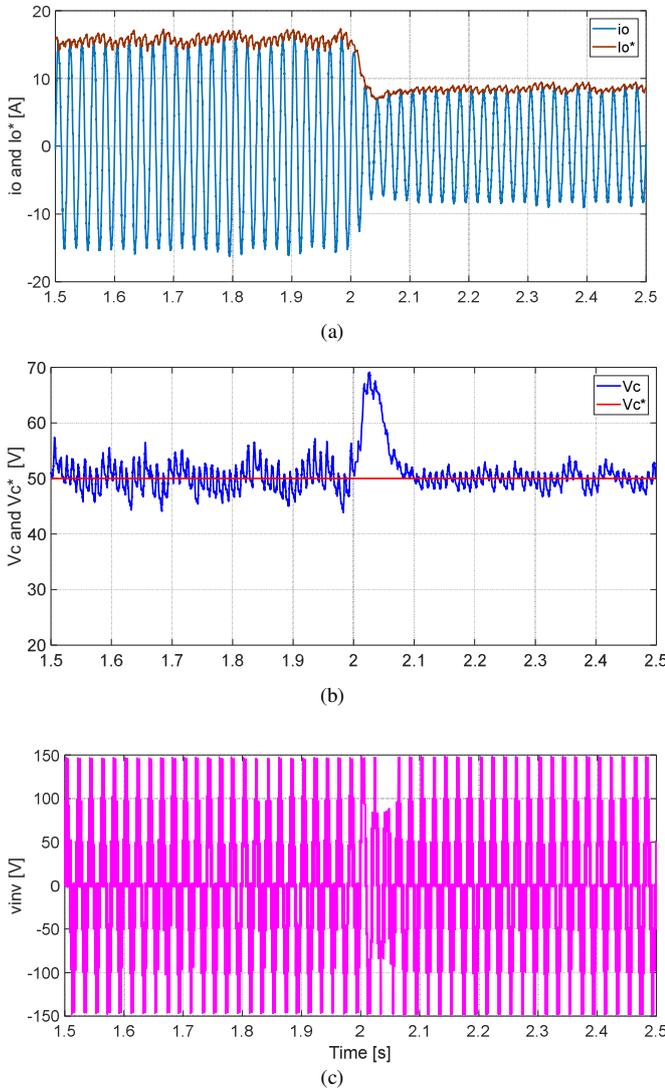

Fig. 8. Dynamic responses of AC and DC variables obtained by the proposed PI-PR based control when R_2 is disconnected suddenly at t=2s. (a) i_o and I_o^* (b) V_c and V_c^*, (c) v_{inv}.

VI. CONCLUSION

A PI-PR based control strategy was proposed for PUC inverters. In the conventional PI-PI based control strategy, while the first PI regulates the DC capacitor voltage, the second PI regulates the AC load current. However, the second PI cannot achieve zero tracking error in the load current due to the fact that PI controllers are not able to achieve zero tracking error for the AC signals. In an attempt to reduce the tracking error by tuning PI gains leads to distortions in the load current. Hence, a PI-PR based control strategy is obtained by replacing the second PI by a PR controller. The performances of both PI-PI and PI-PR control methods have been compared. It is shown that the load current to tracks its reference in all circumstances provided that the inverter current reference is generated accurately. Computer simulations are conducted to show the steady-state and dynamic performances of both control methods.

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