Frequency-PWM hybrid controller of single-switch forward-flyback converter for DC-link regulation of 27-level cascaded H-bridge inverter

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Abstract: Among multilevel inverter topologies, asymmetric Cascaded H-Bridge (CHB) inverters have higher output-voltage levels than symmetrical ones. However, asymmetric multilevel inverters need pre-stage isolated and floating DC power sources, which make the system complicated and bulky. This paper is focused on solving the problem by using a single-core (magnetically-coupled) multiple-output forward-flyback converter as the pre-stage of trinary 27-level asymmetric Multi-Level Inverters (MLI). The forward and flyback converter is driven by a single switch with a controller employing both a PWM duty control and frequency control for continuous conduction mode (CCM) forward output and discontinuous conduction mode (DCM) flyback output respectively. Each output, then, can be regulated independently even though the single switch is used. The proposed system and control method are validated using a 1-kW hardware prototype for the experimental verification.

Keywords: multilevel, asymmetrical, forward-flyback, frequency control, hybrid control, single switch, discontinuous conduction mode

Classification: Power devices and circuits

References


1 Introduction

Recently, Multi-Level Inverters (MLI) have been studied because they have many advantages such as reducing Total Harmonic Distortions (THDs), output filters size, and switch stresses, so on [1, 2, 3]. From the advantages, they have been gradually extended even to small-scale rooftop inverters and building integrated photovoltaic (PV) systems [4]. Among the topologies, Cascaded H-Bridge (CHB) inverters, called multi-cell inverters, are supposed to be the most promising candidate, because they require the minimum number of switches, diodes, and capacitors compared to others, in order to achieve the same number of levels [3]. The CHB structures are generally categorized into two types: symmetric and asymmetric types [1]. Actually, asymmetric CHB inverters can make more levels than symmetric ones, which contributes to the reduction of the THDs, common-mode voltages, output filter size, and the switching losses [5]. Additionally, asymmetric CHB inverter achieves higher efficiency because most of the inverter power is processed through the 50/60-Hz main H-bridge cell [1, 5]. Despite these advantages, however, this topology has a drawback of need of pre-stage isolated, floating, and well balanced. One of the solutions used a multi-winding high-frequency transformer link (HFL) as the pre-stage. This allows the utilization of only single power supply for the 3 H-bridge multilevel inverter drive [5]. However, the HFL topology needs additional switches, diode-bridges, and an extra reset circuit for the ferrite transformer. Another one is using a boost DC-DC module based on a coupled inductor and charge-pump circuit for 27-level inverter [1]. Although this topology can make floating and isolated voltages for feeding each auxiliary H-bridge cell, these voltages produced by coupled inductor of the boost converter is not precisely controlled because the secondary sides are passive-circuited. In the most-recent 7-level CHB inverter, the DC-link voltage is tightly controlled by a flyback converter, and it can be expanded to 27-level with 3 H-bridges as shown in
Fig. 1(a) [6]. However, the single switch cannot control both outputs \((V_{aux1}, V_{aux2})\), but only one of them [7, 8]. This paper is focused on how to achieve the individual DC-link regulation by a single-switch forward-flyback converter for trinary CHB 27-level inverter as shown in Fig. 1(b). The proposed DC-DC pre-stage easily achieves the isolated and floating DC voltages by flyback and forward secondary rectifiers which respond a frequency-PWM hybrid control. The forward output is controlled by the duty ratio of primary switch, also the flyback one is regulated by the switching frequency. This control method provides a tight regulation to both of the H-bridge inputs \((V_{aux1}, V_{aux2})\), independently.

2 Operating principle of cascaded H-bridge 27 level inverter

Fig. 2(a) shows a trinary asymmetric 27-level CHB MLI circuit and 2(b) shows the output voltages which has 27-level of this CHB inverter. The simplest and conventional modulation strategy for this CHB MLI is the nearest level modulation (NLC) [9], being used for this work. The NLC method has two advantages like a low operating frequency and an excellent dynamic performance [5]. Especially, the main HB cell \((V_{dc} \text{ input cell})\) operates at a fundamental frequency \((50/60 \text{ Hz})\) which achieves a high efficiency because of reduction of switching loss. In the higher modulation index, power is processed by the aux1, aux2 cell only 16%, 3% respectively, and most power above 80% is processed by the main [9]. As shown in
Fig. 1, however, two independent, floating, isolated power supplies is needed for upper two HB cells \((V_{dc}, V_{dc}/3, V_{dc}/9)\) in this topology. Next chapter proposes a forward-flyback converter to solve the problems.

3 Analysis of forward-flyback converter

3.1 Basic principle of the proposed dual control

Power stage of the proposed single-transformer forward-flyback converter scheme is shown in Fig. 3(a). The flyback inductor \((L_m)\) current operates in discontinuous conduction mode (DCM) and the forward inductor \((L_{for})\) does in continuous conduction mode (CCM) to supply each load.

![Circuit diagram](image)

*Fig. 3. Circuit diagram (a) magnetically-coupled forward-flyback (b) proposed controller*

In order to regulate both of the input voltages of Aux1 and Aux2 H-bridge cells with single converter switch \(Q\), the proposed control method is needed. As an ordinary PWM control method used to regulate the forward rectifier output \((V_{ofor})\) in CCM, a triangular carrier and a control voltage are needed (See Fig. 3(b)). Then for the flyback output \((V_{ofly})\) regulation in DCM, the triangle carrier generation method is different from the conventional fixed frequency operation. In proposed, the triangular carrier frequency is adjusted by the flyback controller of another proportional-integration (PI) compensator so that the resulting triangle carrier compared to the control voltage (forward PI output) generates a PWM signal in various frequency. Then the multi-output converter has two voltage gains. The gain of the CCM forward converter is (1), that of the DCM flyback converter is (2).

\[
\frac{V_{ofor}}{V_{main}} = ND, \\
\frac{V_{ofly}}{V_{main}} = D \sqrt{\frac{R_{fly}}{2fL_m}} \tag{2}
\]

where \(N\) is the transformer turn ratio between primary (N1) and forward secondary (N3), \(R_{fly}\) is the load of flyback converter, \(f\) is the switch frequency, \(L_m\) is the magnetizing inductance, and \(D\) is duty cycle of the forward-flyback converter. As can be seen, (1) and (2) have the duty ratio \(D\) commonly. As the first design step, \(D\) is determined as independent control variable of the forward converter. Then, \(f\) is considered as the controllable variable with \(R_{fly}\) equivalent to the flyback load, then automatically \(L_m\) is fixed by (2). Then, the dynamic characteristic analysis and the controller design are done. The transfer functions for both of duty-to-forward output voltage and frequency-to-flyback output voltage are newly derived to design the controller in the next section.
3.2 Small signal analysis using state space averaging

The small-signal transfer function of forward converter is similar with buck converter because the forward converter is buck-derived circuit. The duty-to-output voltage transfer function of the forward converter is derived as [10],

\[
G_{vd} = \frac{\dot{v}_{ofor}}{d} = \frac{V_{\text{main}}N}{L_{\text{for}}C_{\text{for}}s^2 + \frac{L_{\text{for}}}{R_{\text{for}}} + 1}. \tag{3}
\]

Next, frequency-to-flyback output voltage transfer function must be considered for the flyback controller design. The transfer function is derived by the characteristics of flyback converter DCM operation assuming that \(\frac{di_{Lm}}{dt} = 0\) because the magnetizing current is zero during \((1 - D_1 - D_2)/f\) as shown in Fig. 4, Mode3. The state equations for mode1, 2, and 3 can be expressed as (4), (5), (6).

\[
\begin{align*}
L_m \frac{di_{Lm}}{dt} &= V_{\text{main}}, & C_{fly} \frac{dv_{fly}}{dt} &= -\frac{V_{fly}}{R} \text{ (mode1)} \tag{4} \\
L_m \frac{di_{Lm}}{dt} &= -\frac{V_{fly}}{n}, & C_{fly} \frac{dv_{fly}}{dt} &= \frac{i_{Lm}}{n} - \frac{V_{fly}}{R} \text{ (mode2)} \tag{5} \\
L_m \frac{di_{Lm}}{dt} &= 0, & C_{fly} \frac{dv_{fly}}{dt} &= -\frac{V_{fly}}{R} \text{ (mode3)} \tag{6}
\end{align*}
\]

Finally, the proposed transfer function is derived as shown below (\(n = N_2/N_1\)),

\[
G_{vf} = \frac{\dot{v}_{fly}}{f} = \frac{-2D_2L_mR_{fly}L_{Lm}V_{fly}}{2FnL_mR_{fly}C_{fly}V_{fly}s + 2nL_mFV_{fly} + 2D_2L_mR_{fly}F_{Lm} + D_1D_2^2R_{fly}V_{\text{main}}} \tag{7}
\]

The derived transfer function is verified by comparing the bode plots as shown in Fig. 5. It can be seen that the transfer function from small-signal modeling matches well with the exact switching model from PSIM simulation. The bandwidths for the frequency-regulation and duty-regulation are 3 kHz and 1 kHz, respectively.
4 Hardware implementation

Verification of the pre-regulated CHB 27-level inverter in the proposed single-switch hybrid control has been done using an 1-kW hardware prototype. Fig. 6 shows an experimental result waveforms of the proposed system. Fig. 6(a) presents the auxiliary input voltages \( V_{\text{aux}1} \) and \( V_{\text{aux}2} \) which maintain \( V_{\text{main}}/3 \) and \( V_{\text{main}}/9 \), fed from the forward-flyback converter output voltages \( V_{\text{ofor}} \) and \( V_{\text{ofly}} \), respectively. \( V_{\text{main}} \) is 120 V, \( V_{\text{aux}1} \) and \( V_{\text{aux}2} \) are 40 V, 13.3 V, respectively. And also 27-level inverter voltage and current at 500 W are presented. Fig. 6(b), 6(c) are presented for the DC-link voltage regulation comparison between the previous flyback-flyback pre-stage (Fig. 1(a)) and the proposed forward-flyback (Fig. 1(b)). When a step load change happens, previous flyback-flyback can not regulate the voltage of \( V_{\text{aux}1} \) accurately because the topology cannot have both of CCM-DCM in the multi-output operation. So, only one control variable (duty cycle) with the single switch is available, thus \( V_{\text{aux}1} \) is less than 13.3 V after the load step. Whereas, the forward-flyback can be controlled by PWM-frequency dual controller. As a result, \( V_{\text{ofor}} \) is regulated by PWM, and \( V_{\text{ofly}} \) is regulated by frequency. Fig. 6(c) shows that the proposed controller properly regulates both outputs under the load step. The THD of the 27-level asymmetric CHB inverter with proposed controller is 2.3%, while that of the conventional flyback is 3.2%.

![Fig. 6. Experimental waveforms (Ch1 is \( V_{\text{aux}2} \), Ch2 is \( V_{\text{aux}1} \), Ch3 is \( V_{\text{inv}} \), Ch4 is \( i_{\text{inv}} \).) (a) Steady-state zoom-in waveforms of the proposed forward-flyback hybrid control at 120 V, 500 W (b) 1 kW–500 W step-load change waveforms with closed loop flyback-flyback (c) 1 kW–500 W step-load change waveforms with forward-flyback hybrid controller]

5 Conclusion

In this paper, a hybrid controller of PWM-frequency variable operation for a cascaded 27-level asymmetric multilevel inverter is presented. The proposed controller allows a reduction of the part count by using forward-flyback as pre-stage converter with single switch. This solution also provides more accurate regulation and high power operation compared with a previous flyback converter system. From the simulation and experimental results with a 1-kW hardware, it is concluded that the proposed system is verified with the output.

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