The Algorithms for Controlling AC Output Voltage of Z-Source Inverter Using Modified SVPWM

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***Abstract* - This paper deals with an algorithm for controlling ac output voltage of Z-source inverter using Modified SVPWM (abbreviated as MSVPWM). Unlike the conventional space vector pulse width modulation, MSVPWM has one extra shoot-through zero time T_{sh}. During shoot-through zero time, both switches in a leg are conducted simultaneously in order to boost inverter output voltage to any desirable value regardless the line voltage. The algorithm to control linearly the capacitor voltage is suggested to improve the performance of Z-source inverter system. The performance of Z-source inverter using above algorithms is demonstrated in simulation results using PSIM.**

***Index terms* - Z-source inverter (ZSI), shoot-through time, three-phase carrier-based PWM, space vector PWM (SVPWM), modified space vector PWM (MSVPWM)**

1. INTRODUCTION

Generally, traditional power inverter is broadly classified as either the voltage-source inverter (VSI) or the current-source inverter (CSI). The VSI and CSI are fed from a dc voltage source or dc current source respectively. Their ac output voltage is limited either lower than the dc input voltage (for a VSI) or greater than dc input voltage (for a CSI). In order to control output voltage in wide range, an additional DC-DC converter should be used on the dc side of the power inverters to support both output voltage buck and boost. In addition, a dead-time circuit should apply to implementation to exclude arm short states

A more recently reported approach is to use the buck–boost ZSI. The ZSI has the same circuit layout as a conventional VSI with the only difference being the use of a unique impedance network between the power source and converter circuit, as shown in Fig. 1. The impedance network consists of two inductors and two capacitors. This impedance network allows both power switches of the same phase-leg to be conducted simultaneously (shoot-through) without short-circuiting the dc source, to boost the dc capacitor voltage and hence the inverter ac output voltage to any desired value regardless the line voltage. In comparison with conventional inverter, ZSI has some more superiority characteristics as follows [1].

- ZSI is a buck-boost inverter. The output voltage is not limited by the input voltage.
- The operation mode of ZSI allows short-circuit across any legs which are banned in conventional inverter.
- Z-source network role of a second order filter and is more effective to suppress voltage and current ripple than capacitor or inductor used alone in the traditional inverter.
- The capacitor and inductor requirements should be smaller than that of the traditional inverter.

With above advance features, ZSI has overcome the conceptual and theoretical limitation of the traditional inverter.

In this paper, MSVPWM (Modified Space Vector PWM) is used to adjust easily the shoot-through time for controlling the ac output voltage of PWM inverter. The algorithm to control linearly the capacitor voltage is suggested to improve the performance of Z-source inverter system. Some simulation results using PSIM are carried out in order to verify the algorithm suggested by the paper.

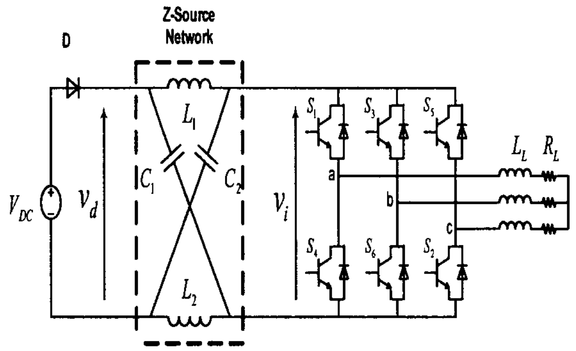


Fig. 1 General configuration of ZSI

2. OPERATION OF Z-SOURCE INVERTER

Fig.2 shows the equivalent circuit of Z-source inverter to explain the operating principle. The operation principle of ZSI can be expressed by two operation modes: Non shoot-through mode and shoot-through mode. The non shoot-through mode consists of six active states when the dc voltage is impressed across the load and two zero states as the load terminals are shorted through either the lower or upper three devices like that of the traditional three-phases VSI as shown in Fig. 3(a). Whereas, the shoot-through mode is a unique mode of ZSI, both devices in an inverter leg are simultaneously conducted in this mode which is forbidden in the conventional inverter as shown in Fig,3(b). This shoot-through mode boosts dc capacitor voltage while producing no voltage to the load.

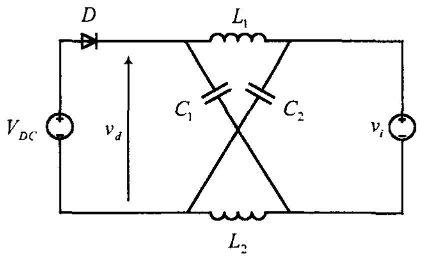


Fig.2 Equivalent circuit for Z-source inverter

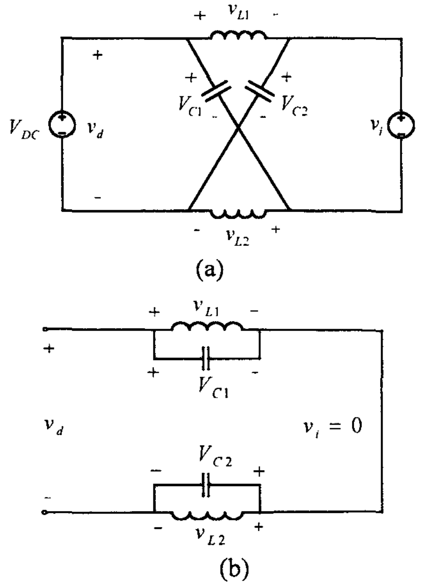


Fig. 3 Operation principle of ZSI

(a) ZSI is in the non-shoot-through mode

(b) ZSI is in the shoot-through mode

In modified carries-based PWM, the shoot-through time can be generated by increasing active time of upper switch whereas on/off time of bottom switch is maintained constant like that of conventional carrier-based PWM. Fig. 4 shows the modified carrier-based PWM with shoot-through time zero state versus conventional carrier-based PWM. The switch-on time of S_1 switch is increased as the on/off time of S4 switch remains constant, for producing the shoot-through zero state.

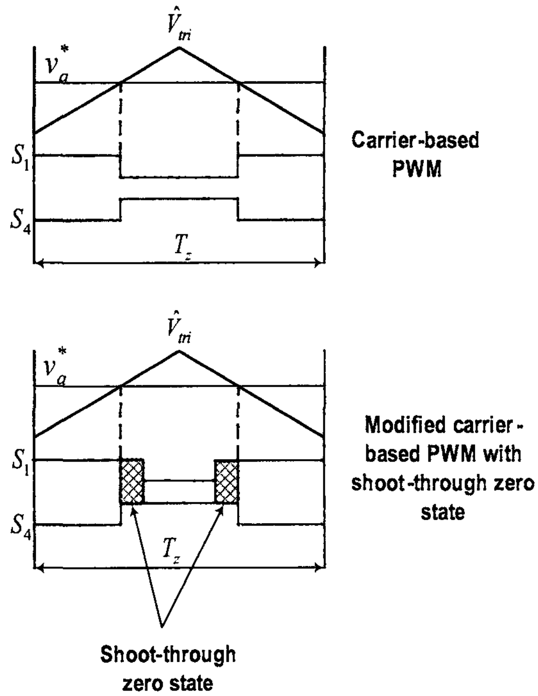


Fig. 4 Modified carrier-based PWM with shoot-through time zero state versus conventional carrier-based PWM

The equations of capacitor voltage and output voltage will be derived [1]. Assuming that inductors L_1 and L_2 and capacitors C_1 and C_2 have the same inductance (L) and capacitance (C), respectively. Thus, the Z-source network becomes symmetric, we have

$$\begin{aligned} v_{L1} &= v_{L2} = v_L \\ V_{C1} &= V_{C2} = V_C \end{aligned} \tag{1}$$

When ZSI is in one of non shoot-through states for an interval of T_n. From the equivalent circuit, Fig. 3(a), one has

$$\begin{aligned} v_L &= V_{DC} - V_C \\ v_i &= V_C - v_L = 2V_C - V_{DC} \end{aligned} \tag{2}$$

Now consider that ZSI is in the shoot-through zero state for an interval of T_{sh}. From the equivalent circuit in Fig. 3(b), one has

$$\begin{aligned} v_L &= V_C \\ v_i &= 0 \end{aligned} \tag{3}$$

The average voltage of the inductors over one switching period T_z becomes to zero in steady state.

$$V_L = \bar{v}_L = \frac{1}{T_z}\int_0^{T_z} v_L dt = \frac{T_{sh}.V_C + T_n.(V_{DC} - V_C)}{T_z} = 0$$

$$\Rightarrow \quad V_C = \frac{T_n}{T_n - T_{sh}} V_{DC} = \frac{1 - T_{pu}}{1 - 2T_{pu}} V_{DC} \tag{4}$$

,where

$$T_{pu} = \frac{T_{sh}}{T_z} \tag{5}$$

$T_z = T_n + T_{sh}$: Switching period

As shown in (4), the capacitor voltage is determined on the shoot-through time T_{sh}.

The peak-dc link voltage across the inverter bridge is expressed as follows

$$\hat{v}_i = 2V_C - V_{DC} = \frac{T_z}{T_n - T_{sh}} V_{DC} = B.V_{DC} \tag{6}$$

where

$$B = \frac{T_z}{T_n - T_{sh}} = \frac{1}{1 - 2T_{pu}} \geq 1 \quad \text{if} \quad 0 \leq T_{sh} \leq \frac{T_z}{2}$$

B is called a boost factor.

It should be noted that the shoot-through state generates zero voltage across to load, and thus preserve the same PWM properties. Therefore, the output peak-phase voltage from inverter can be calculated as

$$\hat{v}_{p\_out} = M\frac{\hat{v}_i}{2} = M.B.\frac{V_{DC}}{2} \tag{7}$$

where

M : Modulation index

Obviously, the output voltage is always obtainable regardless of the line voltage by choosing appropriate modulation index M and boost factor B. Both the shoot-though zero state and two traditional zero states short the load terminals produce zero voltage across the load but the difference is that shoot-through zero states boost the dc capacitor voltage, whereas the traditional zero state do not [2].

As well-known, the general equations in SVPWM are presented below

$$\frac{T_1}{T_z} = \sqrt{3}\frac{V_{ref}}{V_{dc\_link}}\sin(\frac{n\pi}{3} - \alpha)$$
$$\frac{T_2}{T_z} = \sqrt{3}\frac{V_{ref}}{V_{dc\_link}}\sin(\alpha - \frac{(n-1)\pi}{3}) \tag{8}$$

where

T_1, T_2 : durations of applying vectors V_1, V_2 respectively.

n : number of sectors

Furthermore, the relationship between carrier-based PWM and SVPWM is as follows [3].

$$\frac{T_1}{T_z} = \frac{\sqrt{3}}{2}M\sin(\frac{n\pi}{3} - \alpha)$$
$$\frac{T_2}{T_z} = \frac{\sqrt{3}}{2}M\sin(\alpha - \frac{(n-1)\pi}{3}) \tag{9}$$

From (8) and (9), explicitly, the modulation index M relates the reference voltage V_{ref} as.

$$M = \frac{2V_{ref}}{V_{dc\_link}} \tag{10}$$

For ZSI, the average dc-link voltage across the inverter bridge during switching period can be found as capacitor voltage V_C. Therefore, the output peak-phase voltage from inverter is described in term of shoot-through time T_{sh} and reference voltage V_{ref} by substituting (4), (10) into (7).

$$\hat{v}_{p\_out} = M.B.\frac{V_{DC}}{2} = \frac{V_{ref}}{1 - T_{pu}} \tag{11}$$

Substituting T_{pu} in (4) into (11), the peak-phase output voltage can be derived as a function of reference voltage and capacitor voltage.

$$\hat{v}_{p\_out} = \frac{V_{ref}}{1 - \frac{V_C - V_{DC}}{2V_C - V_{DC}}} = V_{ref}\left(2 - \frac{V_{DC}}{V_C}\right) \tag{12}$$

Although the equation (12) originates from (7) but its application is different. The former is concerned with modulation index M, thus it only applies to *ramp comparison method* while the latter handles for *MSVPWM.*

3. MODIFIED SPACE VECTOR PWM

The conventional SVPWM uses eight space vectors $V_0 \div V_7$ to approximate reference voltage or inverter output voltage, where $V_1 \div V_6$ are active vectors and V_0, V_7 are zero vectors. If the reference voltage vector V_{ref} is laying between the arbitrary vector V_i and V_{i+1}, only the nearest two active vectors (V_i and V_{i+1}) and two zero vectors V_0, V_7 should be used. T_1, T_2, T_0 = T_z - (T_1 + T_2) are respective time intervals of two active vectors and zero vectors in one sampling period T_z.[4]

Unlike the conventional SVPWM, MSVPWM has one extra shoot-through zero time T_{sh} beside conventional time intervals T_1, T_2, T_0. During shoot-through zero time, both switches in a leg are conducted simultaneously in order to boost inverter output voltage to any desirable value regardless the line voltage. The time T_0 in MSVPWM should be diminished to generate a shoot through time T_{sh} respectively whereas two active times T_1, T_2 are still maintained like that of conventional SVPWM.

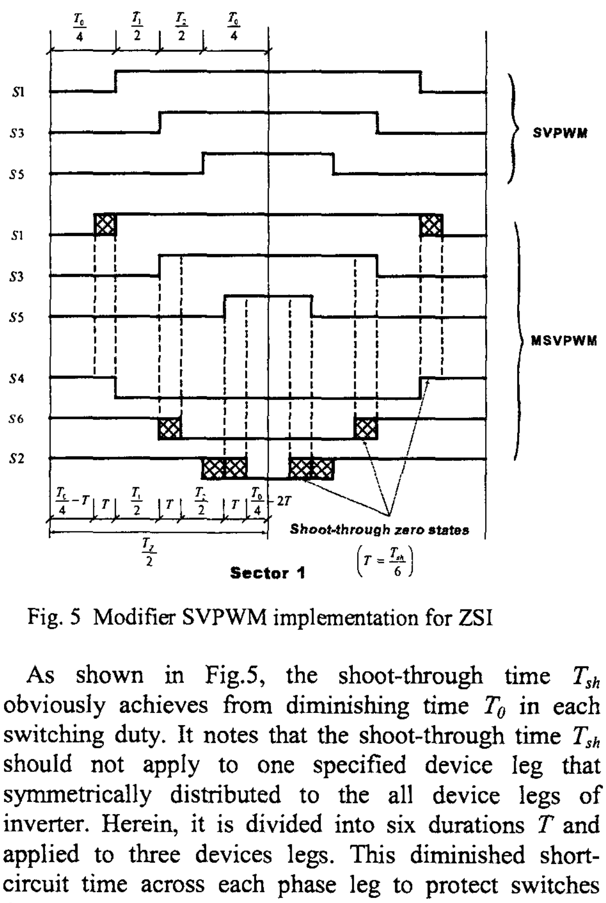


Fig. 5 Modifier SVPWM implementation for ZSI

As shown in Fig.5, the shoot-through time T_{sh} obviously achieves from diminishing time T_0 in each switching duty. It notes that the shoot-through time T_{sh} should not apply to one specified device leg that symmetrically distributed to the all device legs of inverter. Herein, it is divided into six durations T and applied to three devices legs. This diminished short-circuit time across each phase leg to protect switches from high current and not to disturb output waveform. Each switching control signal in MSVPWM is controlled independently each others and only depends on arrangement of shoot-through time of the algorithm.

4. CONTROL SYSTEM

In traditional inverter, the dc-link voltage always equals to dc input voltage and being fixed value. In contrast, ZSI produces a variable dc-link voltage or capacitor voltage V_C via controlling of the shoot-through time T_{sh}. A conventional capacitor voltage controller is shown in Fig.6. The shoot-through time is the output of PI capacitor voltage controller. Unfortunately, from (4), it is apparent that the capacitor voltage V_C does not deal linearly with shoot-through time T_{sh} when the input voltage V_{DC} is fixed. Fig.7 shows the relationship between capacitor voltage and shoot-through time. When the ratio between capacitor voltage and dc input voltage (V_C/V_{DC}) increases from 2 to 8, the ratio (T_{sh}/T_z) only increases from 0.33 to 0.47. Hence, it is hard to obtain a good performance of voltage control with the conventional capacitor voltage controller.

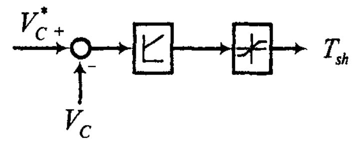


Fig. 6 Conventional capacitor voltage controller

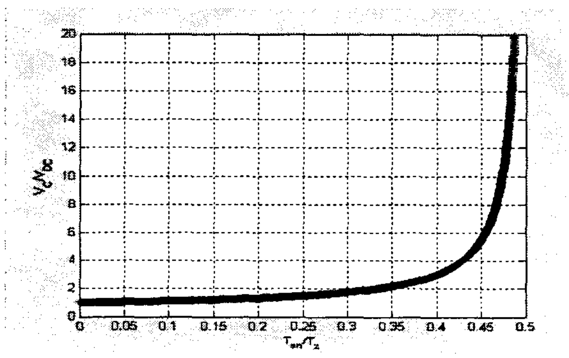


Fig. 7 Relationship between capacitor voltage and shoot-through time

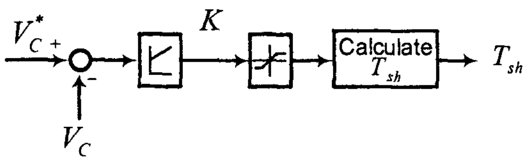


Fig. 8 Capacitor voltage controller using linear method

In order to overcome the problem, a novel algorithm for capacitor voltage controlling is suggested, as shown in Fig. 8. Herein, a factor K is output of PI controller with capacitor voltage error. This factor expresses the relation between capacitor voltage and dc input voltage that proposed in (13). As well-known, K is proportional the capacitor voltage at the input voltage is fixed. In addition, the range of factor K is rather widely, so can be achieved optimal K from presented PI controller. The shoot-through time T_{sh} is calculated through K by using (14).

Using (5), the factor K is determined as follows

$$K = \frac{V_C}{V_{DC}} = \frac{1 - T_{pu}}{1 - 2T_{pu}} \quad (13)$$

and

$$T_{sh} = \frac{K-1}{2K-1} T_z \quad (14)$$

From above analysis, it can realize that the main feature of the algorithm is controlling of capacitor voltage indirectly via the shoot-through time. And some simulation results next section will have justified that the algorithm is feasible and perspective.

The block diagram for controlling ac output voltage in ZSI applying the algorithm is shown in Fig. 9. It consists of three-phase power supply, diode rectifier, Z-source network, PWM inverter and three-phase load. The three phase power supply and the diode rectifier bridge serves as the dc source feeding the Z-source network. The PI controller is in charged of controlling of capacitor voltage. The reference capacitor voltage V_C^* and reference voltage V_{ref} are determined from the designed output voltage $v_{p\text{-}out}$ via equation (12). We can control the reference voltage and the capacitor voltage together to get the desirable output voltage. So, it is easy to control ac output voltage.

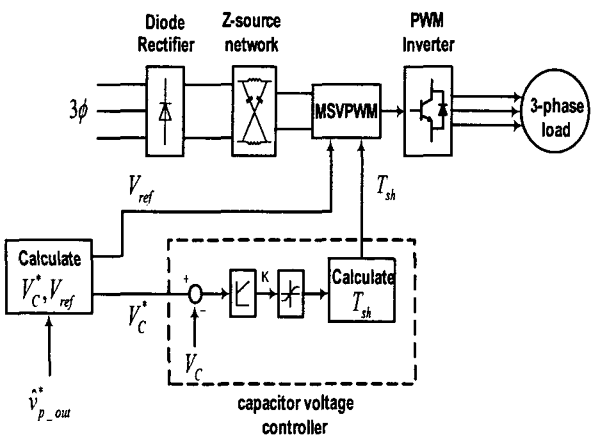


Fig. 9 Block diagram for controlling ac output voltage of the ZSI

5. SIMULATION RESULTS

Some simulations have been carried out by PSIM to confirm the proposed algorithm. The rating and parameters of the system for simulation are given in table.I. An LC filter with 1 kHz cutoff frequency is placed in between the inverter bridge and RL load

Table I. System parameters for simulations

3-phase AC input voltage	V_a = 111 [V], f = 60 [Hz]
Z-source network	$L_1 = L_2$ = 160 [uH] $C_1 = C_2$ = 3 [mF]
3-phase RL load	R = 10 [ohm] L = 10 [uH]
Switching period	T_Z = 200 [usec]

Fig.10 shows the transient responses for capacitor voltage, when the reference capacitor voltage is changed from 300[V] to 350[V] at V_{DC} = 150[V]. It can be seen that the actual capacitor voltage is controlled to its reference value so well. Fig.11 shows the steady-state responses for three phase ac voltages and load currents when the reference capacitor voltage is 350 [V]. The obtainable three-phase output voltage and three-phase load current waveforms after the LC filter are sinusoidal waveforms, and also the amplitude of output voltage is 187.37[V] which is nearly the same theoretical value, 188.57[V]. The theoretical value can be calculated from (12) as

$$\hat{v}_{p\_out} = V_{ref}\left(2 - \frac{V_{DC}}{V_C}\right)$$

$$= 120 \times (2 - \frac{150}{350}) = 188.57[V]$$

The simulation results for ac voltage control will be shown in Fig. 12 and 13, where the desired ac output voltage is 200[V]. After the reference capacitor is decided on 350[V], the reference voltage V_{ref} can be calculated from

$$V_{ref} = \frac{\hat{v}_{p\_out}}{2 - \frac{V_{DC}}{V_C^*}} = \frac{200}{2 - \frac{150}{350}} = 127.3[V]$$

As shown in Fig.12, the capacitor voltage approached to its reference voltage. Fig.13 shows the steady-state responses for reference and real ac output voltages respectively. The peak of ac output voltage is nearly 200[V], which is the desired peak of ac voltage.

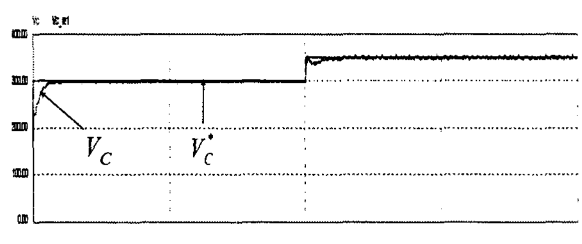
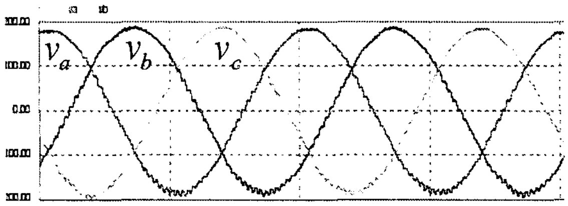
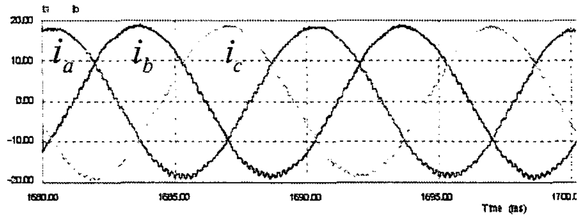


Fig. 10 Transient responses for capacitor voltage.



(a)



(b)

Fig. 11 Steady-state responses at $V_C^* = 350$ [V]
(a) Three-phase inverter output voltage
(b) Three-phase load current.

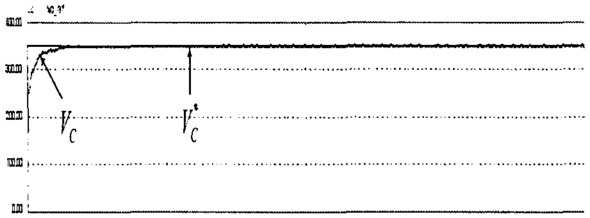


Fig. 12 Transient response for capacitor voltage at $V_C^* = 350$[V]

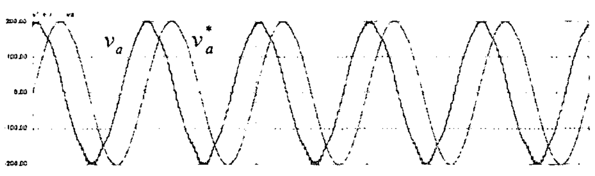


Fig. 13 Steady-state responses for ac output voltage control

6. CONCLUSIONS

This paper has proposed an algorithm for controlling ac output voltage of Z-source inverter using MSVPWM. MSVPWM is used to control ac voltage by adjusting extra shoot-through time T_{sh} beside conventional durations T_0, T_1, T_2. Both the capacitor voltage and also ac output voltage of inverter are boosted to desired value through this shoot-through time. The algorithm to control linearly the capacitor voltage is suggested to improve the performance of Z-source inverter system. Through simulation results, the algorithm suggested by this paper was verified.

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