COMPARISON OF TWO GENERAL CONTROL METHOD FOR THREE-PHASE TO THREE-PHASE AC/AC MATRIX CONVERTERS

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ABSTRACT

This paper presents a complete comparison between two general control method for three-phase to three-phase AC/AC matrix converters. The first algorithm is based on *Least Mean Square Errors (LMSE) method* and the second algorithm is based on *Novel PWM method*. In this paper, the methods are compared from many important points, for example THD, the size of input and output filters, the range of amplitude and frequency of converter, the frequency of switches (thyristor, IGBT, Diode, transistor) and etc. The validity of the aspects is confirmed by the simulation results.

I. INTRODOCTION

The principle of a matrix converter was first proposed in 1980. The matrix converter offers an ***"all silicon"*** Solution for AC/AC conversion. By selective firing of semi-conductor devices it is possible to directly convert alternating current (AC) to alternating current without the need for a direct current (DC) link. The matrix converter as three-phase to three-phase direct converter has number of attractive features such as: sinusoidal input/output currents, power factor adjustment capability and instantaneous power conversion. Matrix converter does not require bulk reactive component, it is mainly electronic conversion technique and therefore potentially can be easily integrated delivering saving in weight and size. In matrix converter, the reactive power and real power can be controlled separately for three-phase input and three-phase output, and the energy flow is bi-directional [1], [2].

II. MATRIX CONVERTER THEORY

A. The Matrix Converter Definition

The three-phase to three-phase AC/AC matrix converter in a schematic form, is presented in Fig. 1, having as inputs the phase voltages v_{i1}, v_{i2}, v_{i3}, and as outputs the phase voltages v_{o1}, v_{o2}, v_{o3}. The "matrix components" S_{11}, S_{12}, …, S_{33} represent nine bi-directional switches capable to block voltage in both directions and switch without delays. The presented matrix converter will connect the three given inputs, with constant amplitude and frequency, through the nine switches to the output terminals in accordance to pre-calculated switching patterns. The obtained outputs three-phase voltage system, have controllable amplitudes and frequency.

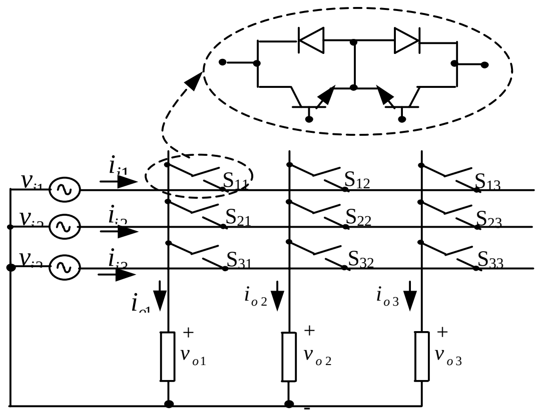

Figure 1. Matrix converter topology

The input voltages of voltage of the matrix converter are given by:

$$\begin{aligned} v_{i1}(t) &= V_i \sin(\omega_i t) \\ v_{i2}(t) &= V_i \sin(\omega_i t - \frac{2\pi}{3}) \\ v_{i3}(t) &= V_i \sin(\omega_i t + \frac{2\pi}{3}) \end{aligned} \tag{1}$$

Where V_i denotes a peak value of input voltages, and ω_i denotes an angular frequency of input voltages.

The matrix converter will be designed and controlled in such a manner that the fundamental of the output voltages are:

$$\begin{aligned} v_{o1}(t) &= V_o \sin(\omega_o t) \\ v_{o2}(t) &= V_o \sin(\omega_o t - \frac{2\pi}{3}) \\ v_{o3}(t) &= V_o \sin(\omega_o t + \frac{2\pi}{3}) \end{aligned} \tag{2}$$

Where V_o denotes a peak value of desired output voltages, and ω_o denotes an angular frequency of output voltages [3].

B. *The first form of control strategy for three-phase to three-phase AC/AC matrix converter*

The three-phase to three-phase AC/AC matrix converter consists of 3x3 switches. The 3x3 switches give 512 combinations of switching states, which are decreased to only 27 permitted states, if the two basic rules to operate this converter safely are applied:

- For prevent of short-circuit of power supplies, do not connect two different input lines to the same output line (over currents);
- For prevent of open circuit of loads (Load is inductive), do not disconnect the output line circuits (over voltages).

Table (I) shows different operating ***Modes*** of matrix converter [3].

TABLE I. The permitted switching states in a three-phase to three-phase matrix converter

MODE	ON SWITCHES	v_{o1}	v_{o2}	v_{o3}
1	S_{11} S_{22} S_{33}	v_{i1}	v_{i2}	v_{i3}
2	S_{12} S_{23} S_{31}	v_{i3}	v_{i1}	v_{i2}
3	S_{13} S_{21} S_{32}	v_{i2}	v_{i3}	v_{i1}
4	S_{13} S_{22} S_{31}	v_{i3}	v_{i2}	v_{i1}
5	S_{11} S_{23} S_{32}	v_{i1}	v_{i3}	v_{i2}
6	S_{12} S_{21} S_{33}	v_{i2}	v_{i1}	v_{i3}
7	S_{11} S_{22} S_{23}	v_{i1}	v_{i2}	v_{i2}
8	S_{21} S_{32} S_{33}	v_{i2}	v_{i3}	v_{i3}
9	S_{12} S_{13} S_{31}	v_{i3}	v_{i1}	v_{i1}
10	S_{12} S_{13} S_{21}	v_{i2}	v_{i1}	v_{i1}
11	S_{22} S_{23} S_{31}	v_{i3}	v_{i2}	v_{i2}
12	S_{11} S_{32} S_{33}	v_{i1}	v_{i3}	v_{i3}
13	S_{12} S_{21} S_{23}	v_{i2}	v_{i1}	v_{i2}
14	S_{22} S_{31} S_{33}	v_{i3}	v_{i2}	v_{i3}
15	S_{11} S_{13} S_{32}	v_{i1}	v_{i3}	v_{i1}
16	S_{11} S_{13} S_{22}	v_{i1}	v_{i2}	v_{i1}
17	S_{21} S_{23} S_{32}	v_{i2}	v_{i3}	v_{i2}
18	S_{12} S_{31} S_{33}	v_{i3}	v_{i1}	v_{i3}
19	S_{13} S_{21} S_{22}	v_{i2}	v_{i2}	v_{i1}
20	S_{23} S_{31} S_{32}	v_{i3}	v_{i3}	v_{i2}
21	S_{11} S_{12} S_{33}	v_{i1}	v_{i1}	v_{i3}
22	S_{11} S_{12} S_{23}	v_{i1}	v_{i1}	v_{i2}
23	S_{21} S_{22} S_{33}	v_{i2}	v_{i2}	v_{i3}
24	S_{13} S_{31} S_{32}	v_{i3}	v_{i3}	v_{i1}
25	S_{11} S_{12} S_{13}	v_{i1}	v_{i1}	v_{i1}
26	S_{21} S_{22} S_{23}	v_{i2}	v_{i2}	v_{i2}
27	S_{31} S_{32} S_{33}	v_{i3}	v_{i3}	v_{i3}

The first form of control strategy for three-phase to three-phase AC/AC matrix converter is based on ***LMSE method***. The difference (Error) between measured and forecasted outputs is E_1, when S_{11}, S_{22}, S_{33} are closed (Mode 1), E_2 when S_{12}, S_{23}, S_{31} are closed (Mode 2), … and finally E_{27} when S_{31}, S_{32}, S_{33} are closed (Mode 27). The equations of E_1, E_2, …, E_{27}, are as follow:

$$E_1(t) = [v_{o1,Forc.}(t) - v_{i1}(t)]^2 + [v_{o2,Forc.}(t) - v_{i2}(t)]^2 + [v_{o3,Forc.} - v_{i3}(t)]^2$$

$$E_2(t) = [v_{o1,Forc.}(t) - v_{i3}(t)]^2 + [v_{o2,Forc.}(t) - v_{i1}(t)]^2 + [v_{o3,Forc.} - v_{i2}(t)]^2$$

$$\vdots$$

$$E_{27}(t) = [v_{o1,Forc.}(t) - v_{i3}(t)]^2 + [v_{o2,Forc.}(t) - v_{i3}(t)]^2 + [v_{o3,Forc.} - v_{i3}(t)]^2$$

This method is based on ***LMSE Method***. In another words we have:

$$IF(\min(E_1, E_2, ..., \; E_{27}) = E_1) \qquad THEN \;\; S_{11} \;\; S_{22} \;\; S_{33} = ON$$

$$IF(\min(E_1, E_2, ..., \; E_{27}) = E_2) \qquad THEN \;\; S_{12} \;\; S_{23} \;\; S_{31} = ON$$

$$\vdots$$

$$IF(\min(E_1, E_2, ..., \; E_{27}) = E_{27}) \qquad THEN \;\; S_{31} \;\; S_{32} \;\; S_{33} = ON$$

The relations between the input currents and the output currents are given by:

$$i_{i1}(t) = \begin{cases} i_{o1}(t) & MODE\ 1 \\ i_{o2}(t) & MODE\ 2 \\ . & . \\ . & . \\ 0 & MODE\ 27 \end{cases}$$

$$i_{i2}(t) = \begin{cases} i_{o2}(t) & MODE\ 1 \\ i_{o3}(t) & MODE\ 2 \\ . & . \\ . & . \\ 0 & MODE\ 27 \end{cases} \qquad (3)$$

$$i_{i3}(t) = \begin{cases} i_{o3}(t) & MODE\ 1 \\ i_{o1}(t) & MODE\ 2 \\ . & . \\ . & . \\ i_{o1}(t) + i_{o2}(t) + i_{o3}(t) & MODE\ 27 \end{cases}$$

C. *The second form of control strategy for three-phase to three-phase AC/AC matrix converter*

The second form of control strategy for three-phase to single phase AC/AC matrix converter is based on the ***novel PWM method***. This method is an alternative **PWM** strategy for matrix converters. In this strategy, the sampling time T_s will be divided in to 3-time intervals t_1, t_2 and t_3 (Fig. 2) [4], [5].

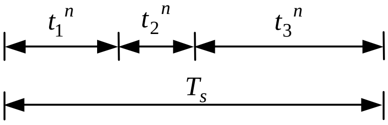

Figure 2: The sampling time, T_s

During any n[th] sampling time T_s related with time intervals t_1, t_2 and t_3 as follows:

$$T_s = t_1^n + t_2^n + t_3^n \tag{4}$$

In this approach, we form the switches matrix, S (eqn. 5).

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{5}$$

In switching approach, at t_1 time interval, the switches in the major-diagonal will be turned on, and the remaining switches will be off, at t_2 time interval, the switches in the minor-diagonal (next to major-diagonal) will be turned on and the remaining switches will be off, and this procedure continues for t_3 time interval. Therefore, the average output voltages can be described as eqn. (6).

$$\begin{aligned} v_{o1}(t) &= \frac{1}{T_s}\{v_{i1}t_1 + v_{i3}t_2 + v_{i2}t_3\} \\ v_{o2}(t) &= \frac{1}{T_s}\{v_{i2}t_1 + v_{i1}t_2 + v_{i3}t_3\} \\ v_{o3}(t) &= \frac{1}{T_s}\{v_{i3}t_1 + v_{i2}t_2 + v_{i1}t_3\} \end{aligned} \tag{6}$$

We see that the combination of input voltages at time intervals t_1, t_2 and t_3 can produce a suitable set of output voltages. For example, $v_{i1}(t)$ only for time interval t_1, $v_{i2}(t)$ only for time interval t_2 and $v_{i3}(t)$ only for time interval t_3 combined together for establishing $v_{o1}(t)$. Based on the above equations, the switching pattern t_1, t_2 and t_3. It is obvious that during n[th] sampling time T_s, the time intervals t_1, t_2 and t_3, must justify the eqn. (4) and also the following equations:

$$0 \le t_i^n \le T_s \qquad i = 1,2,3 \tag{7}$$

In the matrix form, the eqn. (6) can be written as follows:

$$\begin{bmatrix} v_{o1}(t) \\ v_{o2}(t) \\ v_{o3}(t) \end{bmatrix} = \frac{1}{T_s} \begin{bmatrix} v_{i1} & v_{i3} & v_{i2} \\ v_{i2} & v_{i1} & v_{i3} \\ v_{i3} & v_{i2} & v_{i1} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} \tag{8}$$

or simply:

$$[V_o(t)] = \frac{1}{T_s}[V_i(t)] \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} \tag{9}$$

An unique solution of (8) exists when $\det[V_i(t)] \neq 0$. Because of:

$$\det[V_i(t)] = (v_{i1}^3 + v_{i2}^3 + v_{i3}^3) - 3v_{i1}v_{i2}v_{i3} = 0 \tag{10}$$

Therefore infinite number of solution for t_1, t_2 and t_3 existed. To solve this problem, we assume one of times, t_1, t_2 and t_3 and calculate others, here we assume:

$$t_1 = T_s - t_2 - t_3 \tag{11}$$

From eqns. (1), (2), (8) and (11) we have:

$$\begin{aligned} \frac{t_1}{T_s} &= \frac{1}{3} + \frac{2}{3}\frac{V_o}{V_i}\cos[(\omega_o - \omega_i)t] \\ \frac{t_2}{T_s} &= \frac{1}{3} + \frac{2}{3}\frac{V_o}{V_i}\cos[(\omega_o - \omega_i)t - \frac{2\pi}{3}] \\ \frac{t_3}{T_s} &= \frac{1}{3} + \frac{2}{3}\frac{V_o}{V_i}\cos[(\omega_o - \omega_i)t + \frac{2\pi}{3}] \end{aligned} \tag{12}$$

For justify the eqn. (7) we must be have:

$$\frac{V_o}{V_i} \le \frac{1}{2} \tag{13}$$

The relations between the input currents and the output currents are given by:

$$\begin{aligned} i_{i1}(t) &= \begin{cases} i_{o1}(t) & time\ interval\ t_1 \\ i_{o2}(t) & time\ interval\ t_2 \\ i_{o3}(t) & time\ interval\ t_3 \end{cases} \\ i_{i2}(t) &= \begin{cases} i_{o2}(t) & time\ interval\ t_1 \\ i_{o3}(t) & time\ interval\ t_2 \\ i_{o1}(t) & time\ interval\ t_3 \end{cases} \\ i_{i3}(t) &= \begin{cases} i_{o3}(t) & time\ interval\ t_1 \\ i_{o1}(t) & time\ interval\ t_2 \\ i_{o2}(t) & time\ interval\ t_3 \end{cases} \end{aligned} \tag{14}$$

III. SIMULATION RESULTS

The Simulink Matlab and PSpic soft wares are used for simulations. According to the operation principle, the input and output current and voltage waveforms may be determined by the digital simulation method. Ideal switches constitute the matrix converter. The output terminals loaded by a three-phase $R-L$ load $(R = 20^{\Omega}, L = 40^{mH})$. In all matrix converters, the parameters of input voltage source are $V_i = 220^V$ and $f_i = 50^{HZ}$. The models are simulated by two-control method. The relations between the output voltages and the output currents for the three-phase load ($R-L$) are given by:

$$v_{o1}(t) = R\,i_{o1}(t) + L\frac{d\,i_{o1}(t)}{dt}$$
$$v_{o2}(t) = R\,i_{o2}(t) + L\frac{d\,i_{o2}(t)}{dt} \qquad (15)$$
$$v_{o3}(t) = R\,i_{o3}(t) + L\frac{d\,i_{o3}(t)}{dt}$$

From eqns. (2) and (15), the fundamentals output currents are given by:

$$i_{o1}(t) = \frac{V_o}{\sqrt{(L\omega_o)^2 + R^2}}\sin(\omega_o t - \tan^{-1}(\frac{R}{L}))$$
$$i_{o2}(t) = \frac{V_o}{\sqrt{(L\omega_o)^2 + R^2}}\sin(\omega_o t - \frac{2\pi}{3} - \tan^{-1}(\frac{R}{L})) \qquad (16)$$
$$i_{o3}(t) = \frac{V_o}{\sqrt{(L\omega_o)^2 + R^2}}\sin(\omega_o t + \frac{2\pi}{3} - \tan^{-1}(\frac{R}{L}))$$

A) Simulation results for first control method

Figs. 3-6 show the simulation results for three-phase to three-phase AC/AC matrix converter by ***LMSE Method***. The matrix converter controlled in such a way, that the peak value of the fundamental output voltages are $V_o = 210^V$ and $f_o = 100^{HZ}$.

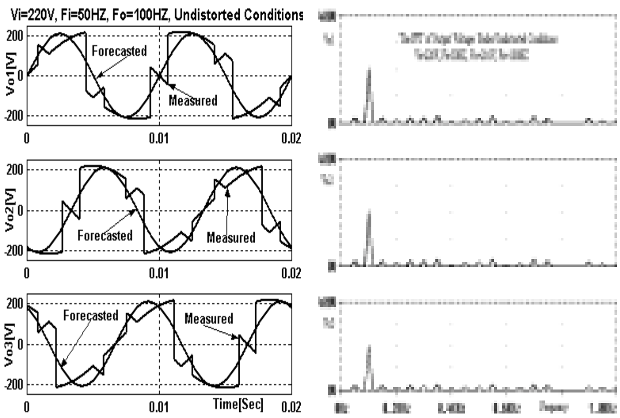

Figure 3: Waveforms of output voltages and their FFTs

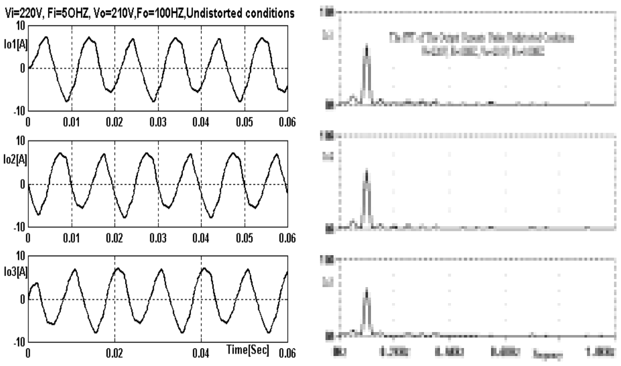

Figure 4: Waveforms of output currents and their FFTs

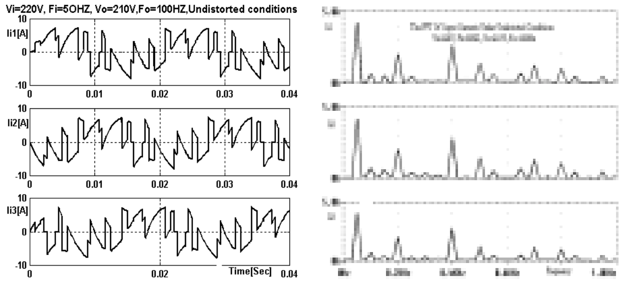

Figure 5: Waveforms of input currents and their FFTs

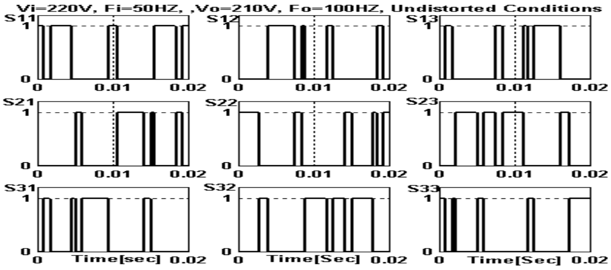

Figure 6: Waveforms of the switches commands

B) Simulation results for second control method

The matrix converter controlled in such a way, that the peak value of the fundamental output voltages are $V_o = 100^V$ and $f_o = 100^{HZ}$. In this case, the converter operated at a switching frequency of 2^{KHZ}. Figs. 7-10 show the simulation results for three-phase to three-phase AC/AC matrix converter by ***novel PWM method***.

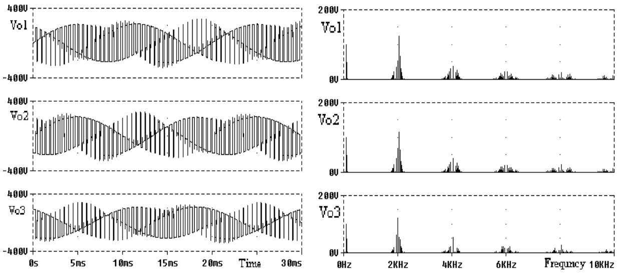

Figure 7: Waveforms of output voltages and their FFTs

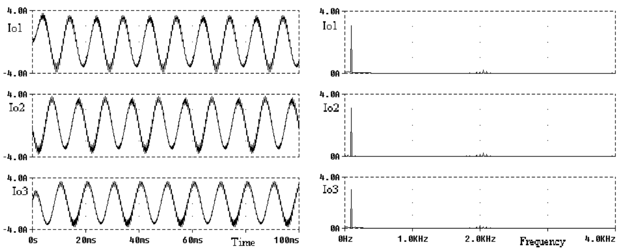

Figure 8: Waveforms of output currents and their FFTs

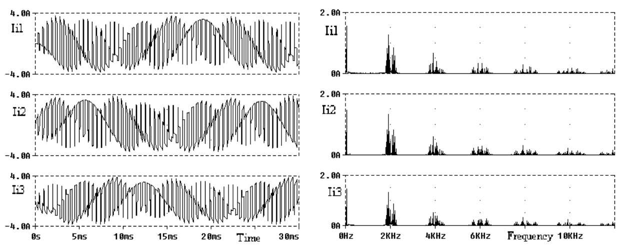

Figure 9: Waveforms of the input currents and their FFTs

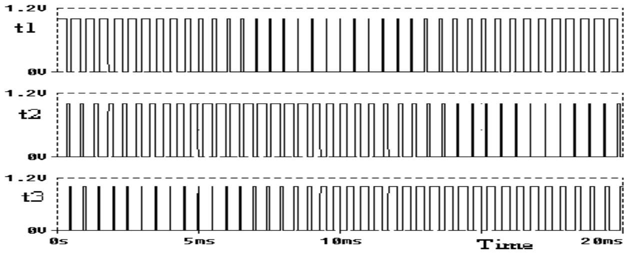

Figure 10: Waveforms of the switches commands

Table (II) shows **THD** of the output voltages, output and input currents for both of method.

TABLE II. The **THD** for both of methods

	LMSE METHOD	NOVEL **PWM** METHOD
v_o	**40.80%**	**187.96%**
i_o	**16.68%**	**10.10%**
i_{i1}	**64.98%**	**189.5%**

IV. CONCLUSIONS

This paper presents a complete comparison between two general control method for three-phase to three-phase AC/AC matrix converters. The first method is based on ***Least Mean Square Errors (LMSE)*** and the second method is based on ***novel PWM method***.

Summery of some results obtained this research:

- Both algorithms ensure that the switches do not short-circuit the voltage sources, and do not open-circuit the current sources.
- Bout algorithms are capable of converting any input waveforms with any given angular frequency, to any output waveforms with any angular frequency.
- The peak value of the instantaneous output voltages for both algorithms is equal with the peak value of input voltages.
- In both algorithms the output voltages contain fundamental and additional high order harmonics.
- In both algorithms the output currents contain high order harmonics.
- Because of the load of the converters is almost always a low pass filter (R-L), therefore the output currents contain loss high order harmonics than the output voltages.
- In ***novel PWM method***, the output voltages contain mainly f_o and $f_s + \Delta f$ Hz harmonics, with Δf being a function of f_i and f_o. For increasing the frequency of harmonics, we should increase the frequency switching, and this needs the high-speed devices. Therefore the losses and cast will be high.
- In ***LMSE method***, the output voltages contain mainly f_o and $f_o + m \times f_i$ Hz harmonics (m is constant).
- The frequency of harmonics for ***LMSE*** algorithm is low, and near the main frequency. Therefore the design of the input and outputs filters will be complicated.
- The ***LMSE method*** is suitable for high output amplitude converting.
- The ***novel PWM method*** is suitable for lower output amplitude converting (see eqn. (13)).
- Simulation results show that the ***LMSE method*** is able to produce the undistorted and balanced output voltages, even if the input supply voltages are distorted and unbalanced [3], and this is not true for the second method.
- The **THD** for ***LMSE method*** is smaller than second method.
- The ***LMSE method*** has easy comprehension of the required commutation process.
- The ***LMSE method*** has simplified control algorithm.
- For ***LMSE method*** as the switches patterns show, because of the number of the switching are very low, therefore by this method the matrix converter has minimum loss.

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