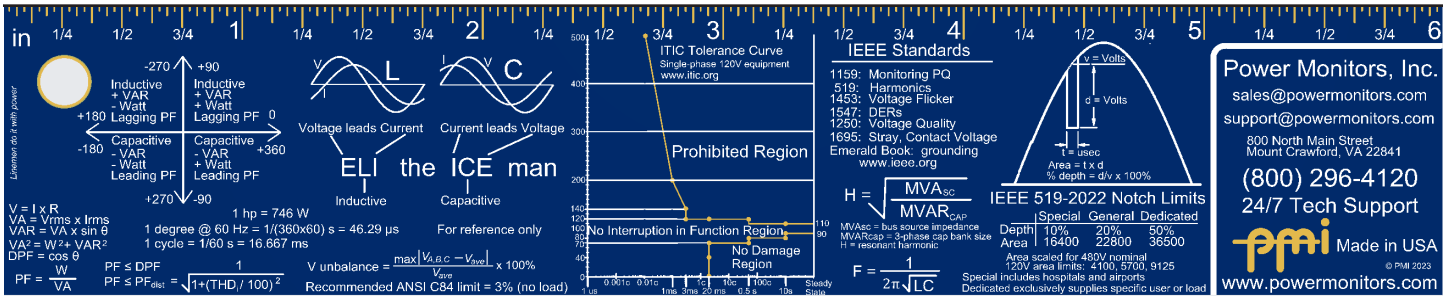
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PMI PQ RULER

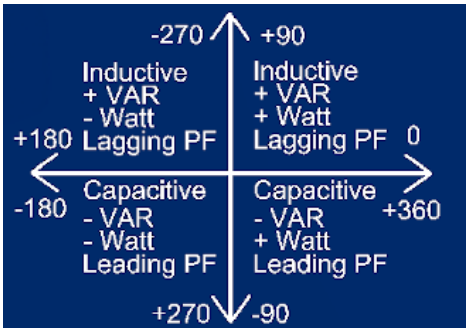


Contributed by Chris Mullins, April 2018

PMI's PQ Ruler is packed with power quality formulas, industry standard limits, tolerance curves, and engineering reference material in the form of a handy 6" ruler. Here the information is unpacked and discussed in more detail. Note that the information on the ruler is highly condensed, and for reference purposes only. The relevant PQ standards should be consulted for background and details.

SIGN CONVENTION

The four quadrant power diagram is shown, indicating the polarity of real and reactive power in the presence of capacitive, inductive, and generating loads. The quadrants, and 0-360 degree span are used in conjunction with the phase angle between voltage and current. For example, the 1st quadrant spans 0 to 90 degrees. As shown in the figure, this is a leading power factor (voltage waveform leads current), with positive real power (Watts) and negative VARs (reactive power). Positive power means the load is consuming power, and the negative VARs means the circuit is capacitive. The most important aspects of the diagram are the positive/negative signs for VARs, and whether it indicates leading or lagging PF.



For more information, refer to Sign Convention for Power Measurements.

OHM'S LAW AND POWER FORMULAS

These are the standard relationships among voltage, current, and power. Ohm's Law, V=IxR, is the key to understanding voltage drop, sags, and any electrical circuit. The formulas for apparent power (VA), reactive power (VAR), displacement power factor (DPF), and power factor (PF) are also given. Reactive power represents energy that transfers back and forth from the utility to magnetic or electric fields in inductive or capacitive loads. Since this energy travels from the utility source and back again, no net work is performed, yet ohmic losses from the extra current contribute to lower voltage and system inefficiency. The apparent power formula derived from real and reactive power holds for 60 Hz only - in the presence of harmonic distortion, the situation is more complex. For more information, refer to Understanding Real Reactive and Apparent Power.

$$V = I \times R$$
$$VA = Vrms \times Irms$$
$$VAR = VA \times \sin\theta$$
$$VA^2 = W^2 + VAR^2$$
$$DPF = \cos\theta$$
$$PF = \frac{W}{VA}$$

PF, DPF AND HARMONICS

True power factor (PF) and Displacement Power Factor (DFP) are both measures of the "efficiency" of power delivery, in the sense that they compare the useful energy delivered to a load vs. the "effort" or "burden" placed on the electrical system by that load. DPF is the 60Hz component of the inefficiency, caused by the phase shift between voltage and current. Poor DPF is traditionally mitigated with capacitors. PF includes the effect of harmonics and is a better overall measure of total efficiency. Since DPF does not include harmonic inefficiencies, it's always greater (better) than PF, or equal to PF if there are no harmonics. PF can be separated into DPF and "distortion" power factor (PFdist), which is the contribution only from harmonics. This can be approximated from the current THD, as shown in the formula.

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For more information, refer to Power Factor vs Displacement Power Factor: What's the Difference?

$$PF \le DPF$$
$$PF \le PF_{dist} = \frac{1}{\sqrt{1+(THD_i/100)^2}}$$

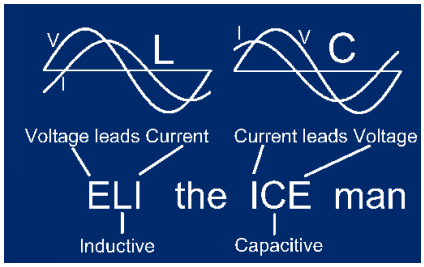
60HZ AND CYCLES

The 60 Hz powerline frequency sets the repetition rate for the AC waveform - 60 "cycles" per second. Each cycle last 1/60 = 0.01666... seconds, or roughly 16.67 milliseconds (ms). When discussing phase angles or phase shift, it's convenient to measure time in degrees, where 360 degrees represents one cycle. Thus, 1 degree = 1/360th of a cycle or approximately 46.29 microseconds.

1 degree @ 60 Hz = 1/(360x60) s = 46.29 µs
1 cycle = 1/60 s = 16.667 ms

ELI THE ICE MAN

This mnemonic is used to recall the relationship between voltage and current waveforms with inductive and capacitive circuits. Traditionally, most distribution circuits are inductive, due to the windings of transformers and motors. With an inductive (L) circuit, the voltage (E) leads the current (I), i.e. the voltage sine wave crosses zero before the current sine wave. This gives "ELI" - voltage (E) is before current (I) in an inductive (L) circuit. "ICE" is the opposite - with a capacitive circuit, current is earlier than voltage.



Generally in power circuits, the voltage waveform is the time reference, and the current is said to lead in a capacitive circuit, and lag the voltage in an inductive circuit.

VOLTAGE UNBALANCE

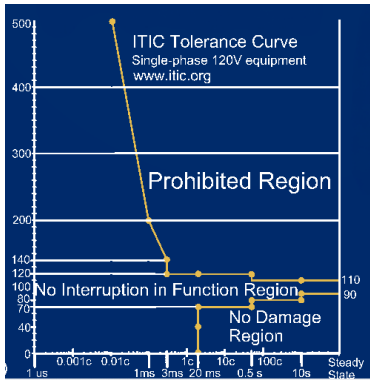
Voltage unbalance is the difference in phase voltage among the three phases, compared to the average, as shown in the formula. Large unbalance (over several percent) can cause excessive heating in motors, VFD controllers, and other 3 phase electronic power supplies. The recommended limit from ANSI C84 is 3%. Voltage unbalance may be local (limited to the secondary of a distribution transformer), mostly caused by unbalanced secondary loading, or present on the primary, caused by unbalanced feeder loading across all three phases.

$$\text{V unbalance} = \frac{\max\left|V_{A,B,C} - V_{ave}\right|}{V_{ave}} \times 100\%$$
Recommended ANSI C84 limit = 3% (no load)

For more information, refer to Measuring Voltage Unbalance.

ITIC/CBEMA

The ITIC graph is used to quantity voltage events, and classify them according to regions as defined by compatibility with computer or other electronic loads. The time scale (x-axis) covers events from 1 microsecond through 10 seconds (and beyond as steady-state). The y-axis, or event magnitude, is given as a percent of nominal. This scale transitions from RMS for longer events, to instantaneous voltage for faster events. An event is plotted as a single point on the graph. Any event inside the two gold lines is in the "No interruption in function" region - computing equipment should not be affected. An event in the "no damage" region may cause a misoperation or shutdown, but not damage. Events in the "prohibited" region may cause equipment damage. The thresholds range from ±10% at 10 seconds and longer, to 500% at the 0.01 cycle (under 170 microseconds) duration.



For more information, refer to CBEMA and ITIC Curves.

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IEEE STANDARDS



The key IEEE PQ standards are listed here. Much of the information on the ruler originates from these documents. Each gives important context, background information, and details on the key pieces shown on the ruler. These should be considered required reading for any power quality professional.

RESONANCE FREQUENCY

A circuit containing a capacitor and inductor will exhibit a resonance frequency, where two reactances cancel. Here, L is the inductance (Henries), C is the capacitance (Farads), and F is the resonant frequency (Hertz). In distribution systems, the capacitance is usually from power factor correction capacitors (PFCs), and the inductance is from transformer windings or inductive loads. Altering the PFC value can shift the resonant frequency if it's causing PQ issues.

$$F = \frac{1}{2\pi\sqrt{LC}}$$

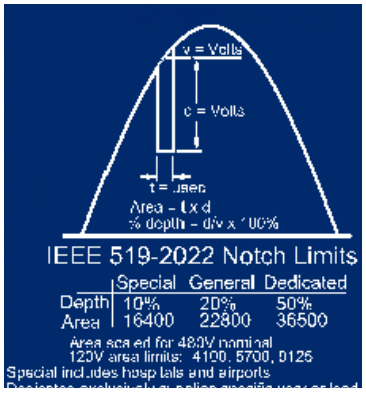
FEEDER RESONANCE FORMULA

Often a feeder PFC is the only significant capacitance on a line, but each transformer and most large loads are inductive and combine to form an aggregate inductance. In theory, the PFC resonates separately with each inductance, and also with each combination of inductances. Many of these closely spaced resonances are seen in practice as one very broad dominant system resonance. This can be approximated by the formula below. As an example, a 20 MVA transformer with a 5% impedance rating will produce approximately 400 MVAsc (short circuit current). If paired with 5 MVAR of PFCs (MVARcap) on the feeder, the resonant harmonic is the 9th (the formula gives 8.94, or 537 Hz). This is a rough approximation but is useful for initial work.

$$H = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}}$$

MVAsc = bus source impedance
MVARcap = 3-phase cap bank size
H = resonant harmonic

VOLTAGE NOTCHING

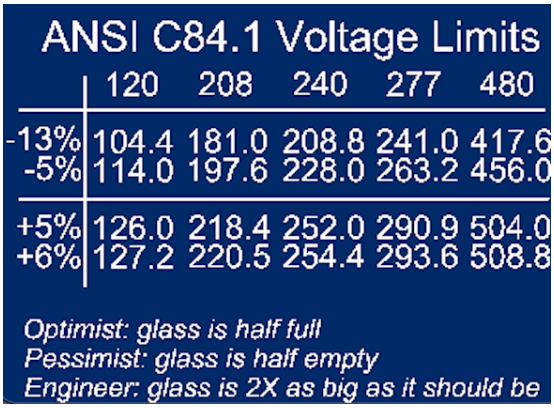


IEEE 519-2014 specifies limits for voltage notching. This is a type of waveform distortion often caused by commutation problems with 3 phase electronic power supplies (such as VFDs), where very high current is drawn at a specific point in the waveform. The unusually high current causes a large, but brief voltage drop each cycle. There are two types of limits: area and depth. The area limit relates to the area of voltage waveform "missing" due to the voltage drop; it affects loads by reducing the energy delivered during that cycle. The depth limit measures the absolute voltage reduction, regardless of duration. Limits are given for three types of locations. The depth limit is a percentage, but the area limit is in absolute volt-seconds, and thus must be scaled proportionally if the nominal voltage is not 480V.

See Voltage Notching in IEEE 519-2014 for more information.

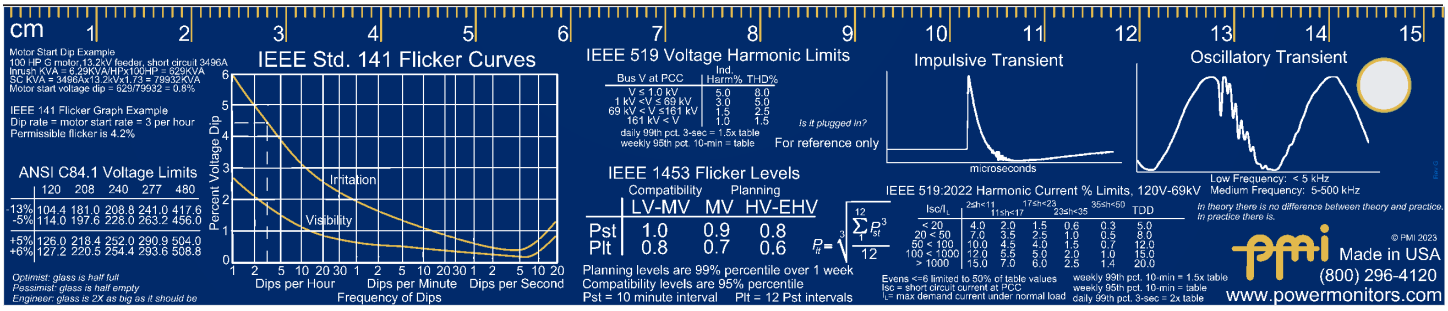
VOLTAGE LIMITS

Allowable steady-state voltage limits are often set at ±5% or ±10%. For example, ANSI C84.1 Range A tolerances are 5%, while NEMA recommends no more than 10% variance from equipment nameplate ratings. These voltages are given here for common nominals of 120, 208, 240, 277, and 480 volts.



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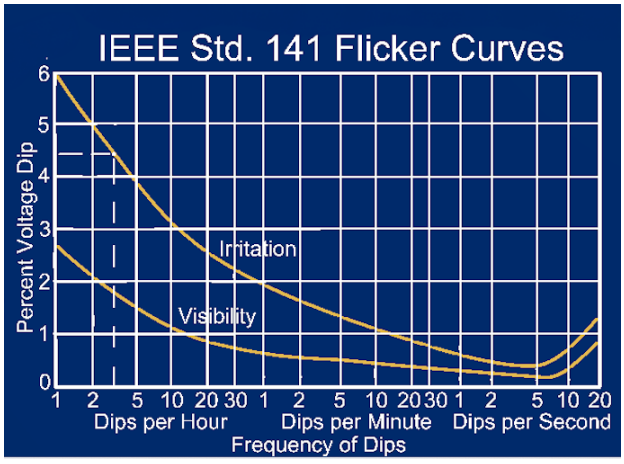
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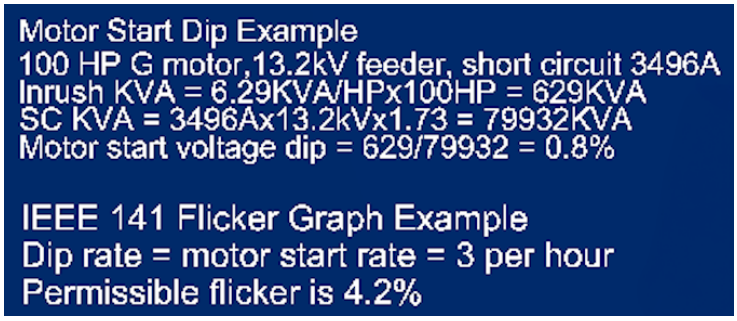
IEEE STD. 141 FLICKER

The original flicker standard, developed from GE, is geared towards periodic on/off load switching ("rectangular modulation" of the RMS voltage), resulting in a certain number of voltage dips per hour, minute, or second, as a percentage of nominal RMS voltage. Two threshold curves are defined. Values above the irritation curve may cause customer irritation, and values above the visibility curve (but below the irritation curve) may noticeable, but typically not irritating.

Two examples are shown to the left of the graph. The first illustrates computing the voltage dip percentage for a large motor, given the motor size and feeder short circuit rating. A NEMA G 100 HP motor with an inrush of 6.29 kVA/HP gives 629 kVA total inrush. The 13.2 kV feeder, with short circuit current of 3496A, gives a short circuit kVA value of 3496x13200x1.73 = 79932 kVA. The voltage dip from the motor will be the inrush kVA divided by the feeder kVA, or 629/79932 = 0.8%. If this motor is started every 2 minutes (30 dips per hour), the flicker is likely to be visible.



In the second example, a dip rate is given as 3 times per hour. The permissible dip permissible dip percentage to avoid exceeded the threshold of irritation is 4.2%. This example is shown with dashed lines on the graph.



In complex cases, or to quantify aggregate flicker from multiple sources, the newer IEEE 1453 flicker standard should be used. The older 141 standard is still useful for estimation with specific loads. For more information, see Application of the GE Flicker Curve and Customizing the GE Flicker Curve.

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IEEE 519 VOLTAGE HARMONIC LIMITS

Harmonic magnitude limits from the IEEE 519-2014 standard are given for different bus voltages. For most customer secondaries, the first row, "V ≤ 1.0 kV" is the most important. The other values are used with primary voltages. To be within compliance, each individual harmonic must be under the limit, as well as the Total Harmonic Distortion (THD). The limits shown are for ten-minute averages and must be met 99% of the time during a one-week period. Limits for three-second averages are 1.5 times the ten-minute values, over a one-day period. It's important to keep in mind that a utility may not be able to meet the voltage harmonic limits if customers are not meeting their recommended current harmonic limits. For more information, see Using the Revolution to Meet the IEEE 519-2014 Standard and A Simplified Approach to IEEE 519 Harmonics.

IEEE 519 Voltage Harmonic Limits

Bus V at PCC	Ind. Harm%	THD%
V ≤ 1.0 kV	5.0	8.0
1 kV <V ≤ 69 kV	3.0	5.0
69 kV < V ≤161 kV	1.5	2.5
161 kV < V	1.0	1.5

Is it plugged in?

daily 99th pct. 3-sec = 1.5x table
weekly 95th pct. 10-min = table

For reference only

IEEE 519 CURRENT HARMONIC LIMITS

The harmonic limits for current are presented in a more complex form than voltage in IEEE 519. Ranges of harmonics have different limits, with the values getting smaller as the harmonic number increases. In the table, "h" is the harmonic number, with 5 ranges spanning the 3rd through the 49th harmonic. Rather than a THD limit, a TDD (Total Demand Distortion) threshold is used. The TDD is essentially a current THD scaled by the largest demand current expected at a location. Except in unusual situations, the TDD is usually much lower than the THD.

The limits are given for various ranges of service types, classified according to the ratio of available short circuit current Isc (at the Point of Common Coupling, PCC) to the maximum demand current, IL. This is a measure of the stiffness of the service, which relates to how current harmonics will result in voltage harmonics.

The limits in the table are for odd harmonics. The even harmonics must be limited to 25% of the odd thresholds. Unlike the voltage limits, these values are for ten-minute averages over 95% of a week period. There are multipliers for 99th percentiles and three-second averages.

For more information, refer to TDD and IEEE 519-2014 and Using the Revolution to Meet the IEEE 519-2014 Standard.

IEEE 519:2022 Harmonic Current % Limits, 120V-69kV

I_{sc}/I_L	2≤h<11	11≤h<17	17≤h<23	23≤h<35	35≤h<50	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Evens <=6 limited to 50% of table values
Isc = short circuit current at PCC
I_L= max demand current under normal load

weekly 99th pct. 10-min = 1.5x table
weekly 95th pct. 10-min = table
daily 99th pct. 3-sec = 2x table

IEEE 1453 FLICKER

The last flicker standard, IEEE 1453, is designed for complex cases, handling non-rectangular modulation and multiple flicker sources. Two key metrics are Pst, the short-term flicker level, and Plt, the long-term level. Pst is normally measured with a ten-minute window, and Plt is a cubic summation of 12 Pst values, as shown on the ruler. "Compatibility" levels are designed to be working limits in field situations. A Pst of 1.0 is roughly equivalent to the threshold of irritation in the older flicker standard; values below 1.0 are generally considered acceptable. The "Planning" levels are targets when upgrading systems or building out new distribution feeders or networks. The lower planning levels give some margin for unexpected flicker sources and future growth. Separate limits are given for low (under 600V, normally customer transformer secondaries), medium (distribution feeders), and high voltage (transmission). The actual limits are given as percentiles over a 1 week time period. For more information, see Understanding IEEE/IEC Flicker Processing and Understanding IEEE Flicker: IFL, Pst, Plt.

IEEE 1453 Flicker Levels

	Compatibility	Planning	
	LV-MV	MV	HV-EHV
Pst	1.0	0.9	0.8
Plt	0.8	0.7	0.6

$$P_{lt} = \sqrt[3]{\frac{\sum_{1}^{12} P_{st}^3}{12}}$$

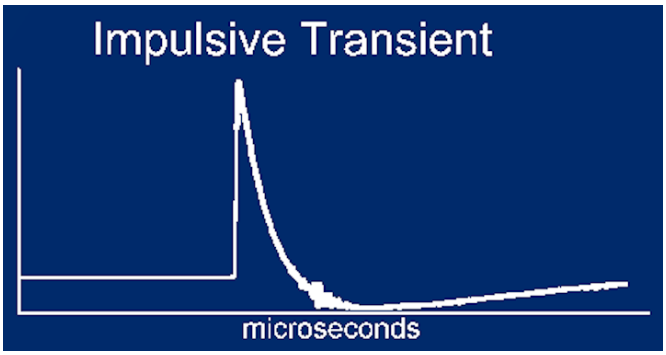
Planning levels are 99% percentile over 1 week
Compatibility levels are 95% percentile
Pst = 10 minute interval Plt = 12 Pst intervals

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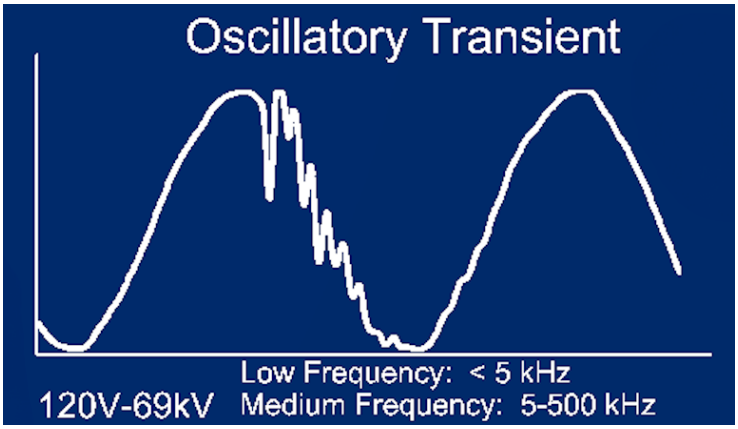
TRANSIENT DEFINITIONS

IEEE 1159 classifies voltage disturbances according to the timescales involved. At the fastest scale are impulsive transients, defined as a "sudden non-power frequency change in a steady-state condition of voltage or current that is unidirectional in polarity." These are typically in the tens of microsecond range, caused by nearby lightning strikes or switching events. The typical distribution impedance attenuates these very quickly, so they don't propagate very far down a power line. A typical impulsive transient is shown on the ruler.



Oscillatory transients are slower in timescale and exhibit a "ringing" shape. These are usually caused by a switching event exciting a system resonant frequency. "Low frequency" oscillatory transients exhibit a ring frequency under 5 kHz, while medium frequency transients are in the range of 5-500 kHz. The most common cause is from PFC switching, where the PFC capacitance "rings" with load inductances.

For more information, see Understanding IEEE 1159 Definitions and Transient Capture vs Waveform Capture.



The PMI PQ ruler gives a very compact distillation of several PQ standards. Brief descriptions of the ruler information have been provided here, with links to whitepapers for more information. It's also important to read the applicable IEEE standards themselves for more background and context.

Call us at (800) 296-4120 to get your free PMI PQ Ruler.

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