LONG-TERM INVERTER OPERATION DEMONSTRATION AT SANDIA NATIONAL LABORATORIES

Sigifredo Gonzalez, Scott Kuszmaul, Abraham Ellis
Sandia National Laboratories

ABSTRACT

The performance of a utility interactive photovoltaic (PV) system relies on several key components within the system. The effects of long term operation on utility interactive inverter performance are the topic of this paper. Years of anecdotal evidence indicates that the PV module typically has a 1% per year degradation in performance; this is accepted by industry for how modules are typically rated and warranted. The inverter on the other hand has not undergone such scrutiny to investigate the effects that years of operation may have on the performance of an inverter. The effects of long-term field operation on utility interconnected PV inverters are the focus of the long term inverter evaluation test bed that is dedicated for years of operation. The outcome of this analysis will be factored into the inverter performance model. Sandia National Laboratories Distributed Energy Technology Laboratory (DETL) has recently completed the first re-characterization phase on inverters operating for two years. This paper reports on the effects of long term inverter operation on four residential inverters.

INTRODUCTION

The DETL has dedicated the necessary PV array resources, access to the utility, and the utility simulator equipment to conduct the initial characterization analysis on each of the inverters under test. A total of nine inverters were involved in the commissioning evaluations and subsequently were installed at three different sites for long term operation and continued performance monitoring. The three host sites are the Southwest Technology Development Institute (Las Cruces, NM), Florida Solar Energy Center (Cocoa Beach, FL), and Sandia National Laboratories (Albuquerque, NM).

The initial characterization of the inverters involved testing using the utility compatibility sections of IEEE 929-2000 IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems [1], UL 1741 Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources [2], and the efficiency and maximum continuous power rating section of the Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems [3]. All evaluations conducted on the inverters and the results from the evaluations adhere to these standards and protocols.

Note: that IEEE 929-2000 was used instead of IEEE 1547 due to the vintage of the inverters.

This paper reports on the effects of long term inverter operation on the four residential inverters installed and operating at the Sandia National Laboratories exposure site.

CONFIGURATION

The long term operation evaluation requires years of continuous operation of the devices under test (DUT) while energized with PV. The PV resource should be sized to supply sufficient power to operate the inverter up to rated power. Dedicating the PV array field to meet these requirements and maintaining the data acquisition system (DAS) that monitors the individual PV systems and finally reducing the hundreds of data files can be a challenge. Sandia has dedicated these resources to achieve the objective of documenting the continued performance of long term operation of utility interconnected PV inverters. A description of the PV system and the data acquisition system are presented below.

The long term inverter operation test bed at Sandia's DETL is comprised of 4 popular residential inverters that are placed outdoors with a south facing exposure as shown in Fig 1. Ideally, the inverters should be placed in a shaded location. However, the primary objective of this experiment is to determine any appreciable degradation in performance and not necessarily to optimize inverter reliability. Therefore exposing the inverters to these extremes was deemed appropriate.

Fig. 1. Long term inverter operation test bed

Inverters 1 and 2, rated at 2.5kW and 3.0kW respectively are connected to individual 3kW standard test conditions (STC) rated PV arrays. The PV arrays are comprised of 2 parallel connected 20-module strings that provide an open circuit voltage (Voc) of ~420 V,

max power voltage (Vmp) of ~340 V and power rating of 3000 Wdc$_{STC}$. Inverters 3 and 4, rated at 2.8kW and 3.0kW respectively are connected to individual 3.5kW$_{STC}$ rated PV arrays. The PV arrays are comprised of 2 parallel connected 22-module strings that provide Voc of ~462 V, Vmp of ~387 V and a power rating of 3520 Wdc$_{STC}$. Table 1 summarizes the inverters used, the amount of PV power that each inverter is connected to and the date each was commissioned.

Table 1 Inverter and array configuration

Inverter	Module Model and Array Configuration	Install Date	Power Level (STC)
Inverter #1	AP-75 2-strings of 20 modules	5/2005	3000 Wdc
Inverter #2	AP-75 2-strings of 20 modules	5/2005	3000 Wdc
Inverter #3	BP 380 2-strings of 22 modules	12/2005	3520 Wdc
Inverter #4	BP 380 2-strings of 22 modules	12/2005	3520 Wdc

The amount of power generated by inverters 1 and 2, connected to the 3kW$_{STC}$ PV array, is included in Figure 2 below; inverters 3 and 4 connected to the 3.52kW$_{STC}$ PV array are shown in Figure 3. The data are 1 minute averages and show the irradiance and ac power versus time.
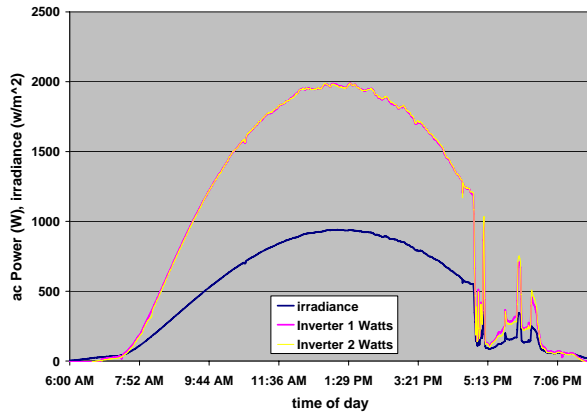

Fig. 2. Inverter 1 & 2 power on typical daily operation

TEST METHODOLOGY

The four inverters underwent a detailed laboratory characterization before being placed outside for long term operation and exposure. The detailed characterizations include utility compatibility evaluations as described in UL 1741 and IEEE 929-2000 and the inverter performance characterization as described in the CEC Inverter Performance Protocol.
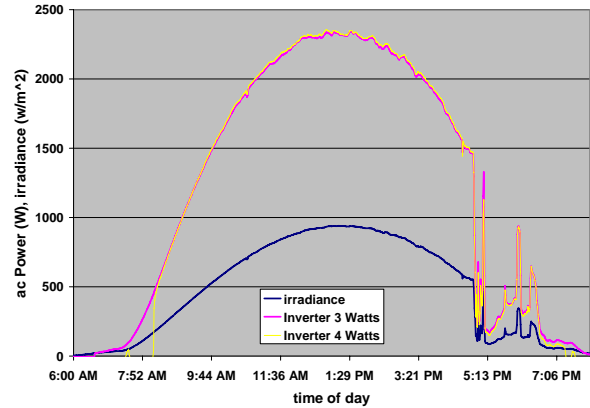

Fig. 3. Inverter 3 & 4 power on typical daily operation

Utility Compatibility Evaluations

Photovoltaic utility interconnect inverters are allowed to connect and energize the utility if the inverter has been evaluated and listed by a nationally recognized testing laboratory (NRTL) and found to adhere to the utility interconnection requirements defined in IEEE 929-2000. Again, IEEE 929-2000 is used instead of IEEE 1547 because of the vintage of the inverters. The majority of the evaluations listed in these standards are conducted on the inverter except the loss of utility requirements. The test procedure can cause transients at the point of common coupling (PCC) that may permanently affect the operating characteristic of the inverter or stop the inverter from operating altogether. Table 2 lists voltage anomaly levels and the reaction criteria against which each inverter was tested.

Table 2 Utility abnormal voltage requirements

Voltage (at PCC)	Maximum Trip Time[1]
V < 50%	6 cycles
50% ≤ V < 88%	120 cycles
88% ≤ V ≤ 110%	Normal operation
110% < V < 120%	120 cycles
120% ≤ V	2 cycles

1 Trip time refers to the time between the abnormal condition being applied and the inverter ceasing to energize the utility line.

Additional inverter features documented during the detailed laboratory characterizations of the inverters undergoing the long term inverter evaluation include power quality and array utilization information. The ac voltage and frequency range evaluations determine at what point the inverter detects an out of specification condition and ceases to energize the utility. The abnormal voltage levels described in Table 2 determine how quickly the inverter is required to respond to an out of specification condition. Emphasis is placed on monitoring the voltage parameter since the voltage measurement circuitry is typically determined using passive components and can be prone to drift after long term exposure to temperature fluctuations and to

electrical anomalies. Table 3 shows a list of the evaluation parameters for one of the inverters including power quality, array utilization and conversion evaluations and compares the manufacturer's specifications to what was measured and recorded with the DAS.

Table 3 Inverter specification requirements *(example)*

Parameter	Manufacturer's Specs	Measured Values
Maximum Rated Power	2700W	2760W
Average Peak Efficiency	94.4%	94.7%
AC Operating Range	212 – 264V	220 – 265V
Frequency Range	59.3 – 60.5Hz	59.5 – 60.4Hz
Power quality	< 5%	< 4%
CEC Efficiency	> 94%	94%
Array utilization	N/A	> 96% all power levels

Inverter Performance Characterization

The performance of the inverter is the most important characteristic to analyze during long term operation. Any appreciable decline in performance will be factored into the inverter model [4]. For the purpose of the model, performance is being restricted to power conversion efficiency.

The inverter performance characterization as described in the CEC inverter performance protocol [3] includes the weighted efficiency measurements and the maximum continuous power rating evaluation. This evaluation is accomplished with the inverter operating at a set of prescribed conditions that influence the efficiency of the inverter. These conditions are the operating dc voltage and the power level, documented using specific dc voltage and power settings. Table 4 shows an example of the desired dc voltage and the desired dc power level and associated conditions.

Table 4 CEC weighted efficiency evaluations

Test	V_{DC}	Inverter DC Input Power Level					
		10 %	20 %	30 %	50 %	75 %	100 %
A	V_{nom}	3.6	4.7	11.4	19.9	50.1	4.7
B	110% V_{min}	3.6	4.7	11.3	19.8	50.0	4.7
C	90% V_{max}	3.5	4.6	11.2	19.7	49.5	4.7

The following are conditions for conducting these tests.
   a. Tests done with MPPT disabled
   b. Test done at nominal frequency (60 Hz) ±1%.
   c. All voltages and currents are measured at the input or output terminals of the inverter.
   d. Vnom = Manufacturer specified nominal operating dc or the average of Vmin and Vmax.

   e. Vmin = Manufacturer specified minimum operating dc voltage.
   f. Vmax = Manufacturer specified maximum operating dc voltage.
   g. 110% of Vmin and 90% of Vmax conditions are selected to provide performance at low and high voltages

The weighted efficiency calculation places a value to each of the 6 power levels shown in table 4. The weighted efficiency calculation serves to assign a value that corresponds to the amount of time that an inverter resides in a particular operating range over the course of a day. This approach addresses installations and conditions where an inverter is oversized for the system or the solar resource is marginal. In these conditions, the weighted efficiency calculation would represent the performance of the system more accurately than the single point efficiency method. Below is an equation showing the weighted values placed on each of the efficiency values at their respective power levels.

$$\eta_{DUT} = 0.04 \cdot \eta_{10} + 0.05 \cdot \eta_{20} + 0.12 \cdot \eta_{30} + 0.21 \cdot \eta_{50} + 0.54 \cdot \eta_{75} + 0.05 \cdot \eta_{100}$$
(1)

Maximum Continuous Power Rating

The rating of an inverter is also determined in the CEC Inverter Performance Protocol [3]. The inverter's maximum power rating is determined under high ambient temperature conditions and for a duration that will typically detect an insufficient thermal mitigation capability of the inverter. This parameter is subject to environmental conditions, making it difficult to quantify. Hence, this parameter will not be considered as part of the inverter performance model parameters.

Data Acquisition

Determining the inverter's performance characterization after long term operation requires that the inverter's performance first be characterized in a controlled environment and under similar operating conditions. The parameters that most influence the inverter performance are the dc voltage level, power level, and ambient temperature. The ambient temperature was held at 25 °C during laboratory characterization evaluations.

Sandia's DETL DAS is LabView-based with an A/D digitizer that utilizes the analog signals from the voltage and current probes and calculates the voltage and current values. LabView subroutines called virtual instruments are utilized for power quality and power calculations. The following equipment was used to conduct the initial characterization of the inverters

LabView DAS Equipment
   • 1.2MS/s 16 bit A/D PCI digitizer

- 4-slot chassis with 4-SCXI 1100 32-channel multiplexing with signal conditioning cards

DC Monitoring
- Tektronix P5200 High Voltage Differential Voltage Probe (monitors dc voltage)
- Empro Shunt with OSI isolation amplifier

AC Monitoring
- Tektronix P5200 High Voltage Differential Voltage Probe (monitors ac voltage)
- Pearson 110A CT (monitors ac current)

To ensure accurate and reliable data, an end-to-end calibration is conducted and any necessary adjustments to the offset and scale factors are made to make the voltage and current equal the standard settings. The voltage and current signals from the standards are generated at unity power factor and at a desired phase angle to calibrate the power calculating subroutines in LabView.

PRELIMINARY BASELINE COMPARED TO THE 2-YEAR ASSESSMENT

The nine inverters that were characterized in the laboratory setting were sent to the three locations for long term operation and exposure. Of the nine inverters, four stayed in Albuquerque, NM, two went to Cocoa Beach, FL, and three went to Las Cruces, NM. The requirements for this study are for the inverters to be operating with sufficient PV to allow the inverter to reach maximum power during some time of the year. The two sites in NM had sufficient power for this to occur but the FL site did not have the resources to operate the inverters at the required power levels. Additionally, one of the FL inverters stopped functioning.

The seven inverters that remained in New Mexico generated the most information for this report and will be used to evaluate the effect of long term use and exposure on the performance of these residential PV inverters. A one-line diagram (see Fig. 4) indicates the transducer placement and the overall configuration.
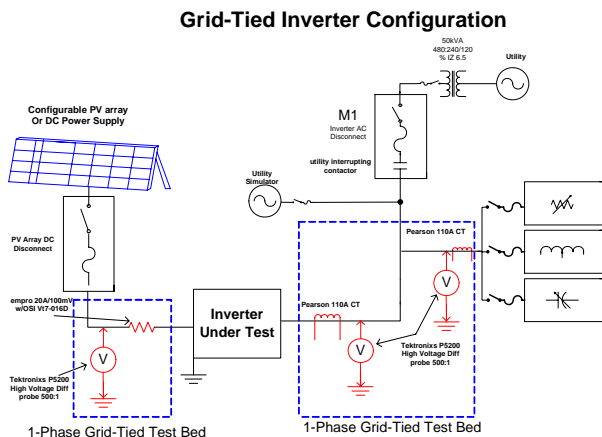
Grid-Tied Inverter Configuration

Fig. 4. One-line inverter characterization

Inverter Re-characterization Comparison

The inverters have been operating on PV since late 2005 with a re-characterization of the inverters conducted in late 2007. For these evaluations the inverters were operated with the same voltage sources and as close to the original voltage setting as possible. Since the inverters are characterized at three dc voltage levels and at 6 power levels, the inverters have to be placed in constant voltage mode during the re-characterization. This means the maximum power point tracking (MPPT) algorithm must be disabled so that the power source current can be limited to achieve the desired output power level at a constant dc voltage. This requires cooperation between Sandia and the various manufacturers for the necessary control functions to disable the MPPT.

The re-characterization of the inverters included the following parameters. However, only the last two parameters are being considered to refine the inverter model, if significant performance degradation is detected.

- Low voltage range evaluation
- High voltage range evaluation
- Low frequency range evaluation
- High frequency range evaluation
- Voltage anomalies evaluations
- Frequency anomalies evaluations
- Efficiency at 3 dc voltage levels
- Maximum power rating evaluations

Efficiency Comparisons

The four inverters from Sandia's DETL and the three from SWTDI were brought back into the lab for controlled laboratory re-characterization. All evaluations conducted as part of the initial characterization were repeated on the units using the same sources, loads, and settings from the previous analysis.

Data collected from the re-characterization of each inverter was compared to the results from the previous evaluations. If the results of the analysis of the power conversion efficiency indicate a substantial degradation in performance, then this decrease in performance over time will be included in the inverter performance model. The comparisons of the evaluations are shown in Figs. 5-8. To minimize the number of plots, the evaluations at different dc voltage levels from both the re-characterizations and the initial evaluation data are combined. This creates a busy but informative plot. The four plots shown are from the four inverters located at the Sandia's DETL facility. Following the plots, Table 5 shows the comparisons of the two evaluations and the percentage change.
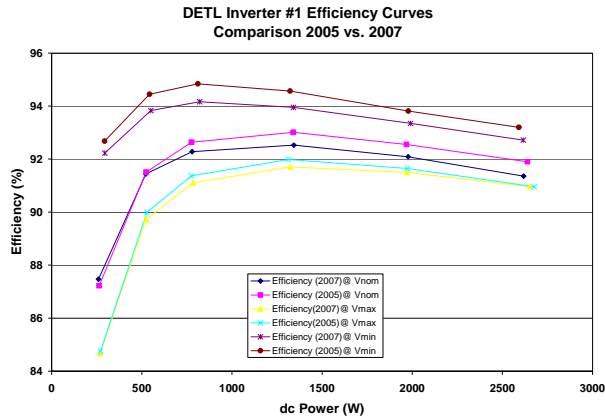
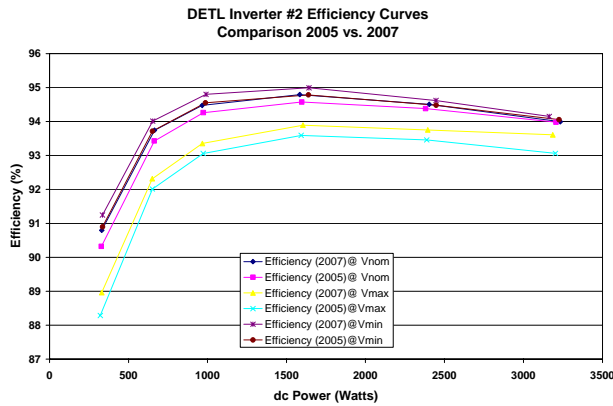Fig. 5. Inverter #1 efficiency curves at different voltages for 2005 and 2007 comparison

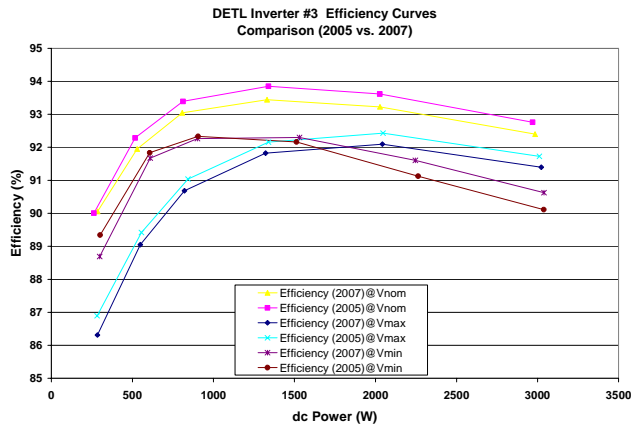Fig. 6. Inverter #2 efficiency curves at different voltages for 2005 and 2007 comparison

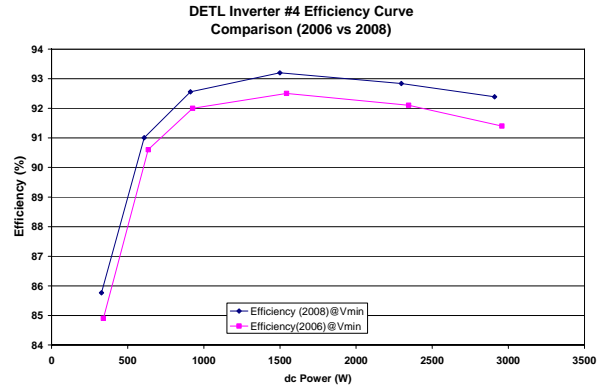Fig. 7. Inverter #3 efficiency curves at different voltages for 2005 and 2007 comparison

Fig. 8. Inverter #4 efficiency curves at minimum dc voltage for 2006 and 2008 comparison

The efficiencies for each of the inverters were determined at different dc voltage and power levels. Efficiencies at different power levels were not conducted on inverters #4 and #7 since communication privileges were not granted to disable the MPPT function to allow the multi-voltage evaluations to occur. The weighted efficiency was calculated for each inverter and a percentage change in the initial performance to the performance after 2 years of operation is shown in Table 5. It should be noted that the percent changes indicated in Table 5 are less than the ±1% typical measurement error and are therefore actual degradation is inconclusive at this point in the long-term test.

Table 5. Weighted efficiency comparison changes

Inverter # DETL	2005 weighted η	2007 weighted η	% change
1	93.9%	94.1%	0.24%
2	92.6%	92.2%	-0.43%
3	92.2%	92%	-0.22%
4	91.8%*	92.5%*	0.76%*
SWTDI			
5	92.4%	91.9%	-0.54%
6	92.3%	91.9%	-0.37%
7	91%*	90.7%*	-0.33%*

*Inverters evaluated at only 1 dc voltage instead of 3

INVERTER PERFORMANCE MODEL

The Performance Model for Grid-Connected Photovoltaic Inverters [4] was developed to provide system integrators, designers, and investors with a tool that will predict the output power of a grid-connected PV inverter given an input PV source. The model was developed to easily implement refinements as more data is available, such as inverter degradation after long term operation and exposure. The inverter performance model is not an electrical circuit model but rather an empirical model that accurately determines the

performance characteristics of the dc to ac conversion process.

The empirical model (equations 1-4) requires accurate, reliable, and representative data to determine the coefficients needed to relate the inverter's ac-power output to both the dc-power and the dc-voltage. Parameters with the 'o' subscript are constant values that represent nominal operating conditions and are obtained from manufacturers supplied specification sheet or the CEC List of Eligible PV Inverter Equipment [5] which provides much of the needed information. See reference [4] for parameter descriptions.

$$Pac = \{(Pac_o / (A - B)) - C \cdot (A - B)\} \cdot (Pdc - B) + C \cdot (Pdc - B)2 \quad (1)$$

where:

$$A = Pdc_o \cdot \{1 + C1 \cdot (Vdc - Vdc_o)\} \quad (2)$$
$$B = Ps_o \cdot \{1 + C2 \cdot (Vdc - Vdc_o)\} \quad (3)$$
$$C = C_o \cdot \{1 + C3 \cdot (Vdc - Vdc_o)\} \quad (4)$$

Model Performance

Several DAS's at Sandia's DETL have implemented the inverter performance model for validation purposes. Figures 9 and 10 show the data from measured and modeled ac power outputs and the total energy harvest for one day. The data shows that the modeled power produced by the inverter agrees very closely to that measured (Fig. 9). The energy harvest of the day is a good measure on the accuracy of the model as compared to that measured on the DAS (Fig. 10).
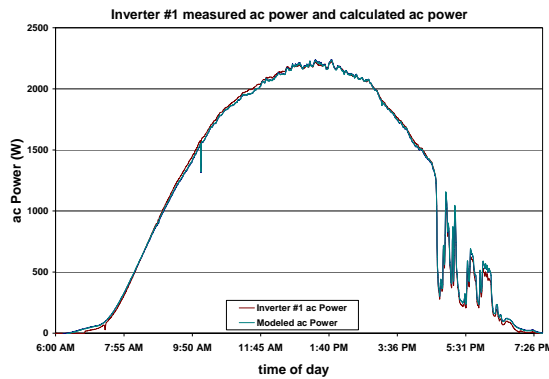

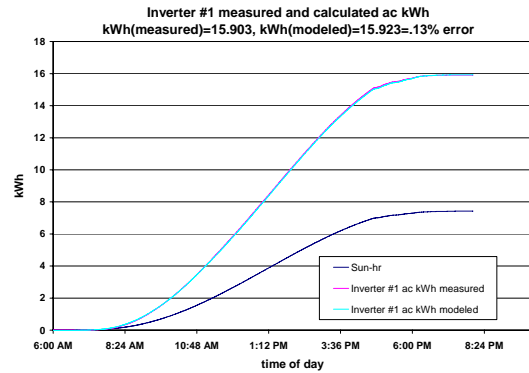Fig. 9. Daily operation-measured and modeled ac power

Fig. 10. Measured and modeled daily energy harvest.

Future Work

The DETL will continue to assess the performance of the inverters involved in the long term operation and exposure study. All seven remaining inverters will undergo another detailed laboratory evaluation in the coming year.

SUMMARY

The first 2 years of operating the inverters with sufficient rated power during exposure to the elements has shown little effect on the performance of the inverter. The worst case was a 0.8% change in the efficiency value of an inverter that had only a single efficiency value obtained. This relatively low change in performance is inconclusive at this point in the test regiment and thus no determination can be stated yet as to whether long term operation of inverters lead to degradation in power conversion performance. However, this result does support the importance of continued long-term performance characterization studies of fielded inverters.

ACKNOWLEDGEMENTS

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