Implementation of Generalized Photovoltaic System with Maximum Power Point Tracking

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***Abstract*—Renewable Energy (RE) resources have vast sustainable potential to meet the increasing global energy demand. Photovoltaic (PV) is one of the most promising RE technologies. Most of the PV systems use specific PV model with fixed parameters. This paper presents a PV system consisting of PV model having generic parameters, PV array, Maximum Power Point Tracking (MPPT), DC/DC converter, DC/AC inverter and synchronization with grid in Matlab/Simulink. There are many MPPT techniques which are used to track the maximum power point of PV systems. We have implemented Perturb and Observe (P&O) algorithm for MPPT. The maximum power point of PV keeps on changing with varying environmental conditions such as solar irradiance and cell temperature. The MPPT extracts maximum power point of PV array and feed it to the load via boost converter. The PV array characteristics and MPPT performance under abrupt change of weather conditions are analysed. Finally, the synchronisation of inverter with grid has been implemented with feedback system. Simulation results prove the effectiveness of the proposed method.**

***Index Terms*—Renewable Energy; Photovoltaic; MPPT; Boost Converter; Perturb and Observe (P&O); Space Vector Pulse Width Modulation (SVPWM)**

I. Introduction and Literature Review

Rapidly increasing electricity demand and atmospheric variations have increased the importance of Renewable Energy Resources (RERs) for sustainable development. RERs are based on natural sources like wind, sunlight, tides etc. These are economical and viable with less carbon emissions and can be certainly replenished [1], [2]. Among several RERs, the solar radiant energy is an abundant and easily available source. Solar energy has offered favourable outcomes to solve power sector problems [3], [4]. Solar energy depends on the climatic conditions like temperature, solar irradiation etc. and consequently it varies continuously. This makes the nature of solar energy intermittent [5].

The output characteristics of Photovolatic (PV) modules depend on solar irradiation and cell temperature [6]. PV modules have nonlinear electrical characteristics hence designing and simulation of the system need reliable PV modeling. Many PV system models have been proposed in order to improve efficiency and performance of the system [7]. R. Falinirina proposed a system with emphasis on PV system, modelling and simulation of PV array, Maximum Power Point Tracking (MPPT) control and DC/DC converter [8]. Performance of the proposed system has been analysed and evaluated using Matlab. However, synchronisation with the grid has not been implemented. Lipika et al. have proposed another system performance of PV module that is optimized Perturb and Observe (P&O) method using buck boost converter [9]. N. Agarwal presented Matlab/Simulink based model to study the case for adaptation of solar energy. Authors have implemented two different types of MPPT controllers to compare effectiveness of both the controllers for PV systems. The proposed system has numerous advantages: simple, reliable, permits simulation of cells etc. and it also analyses incompatible panels which operate under different conditions [10].

This paper presents a PV system consisting of PV model having generic parameters, PV array, P&O algorithm based MPPT, DC/DC converter, DC/AC inverter and synchronization with grid in Matlab/Simulink. Matlab/Simulink provides an intelligent, modular and graphical simulation environment for the constantly varying analysis of Power systems. It also helps in the designing and simulation of power system. Our system proposes an improved PV system as compared to the work of Falinirina in [8]. This work includes PV modeling with generic parameters. The generic PV model provides a user friendly interface to define various PV parameters. This capability enables the users to analyse the PV system having any kind of PV modules. Furthermore, DC to DC converter along with the MPPT controller has also been implemented. Results show that MPPT in PV module successfully tracks the maximum power point of PV array under abrupt changes of solar irradiance, temperature and variable load. Our second major contribution is the implementation of PV system

synchronization with grid. We have implemented three phase inverter and synchronized it with grid using Space Vector Pulse Width Modulation (SVPWM) technique.
Rest of the paper is organized as follows. Proposed model has been elaborated in section II. Results and discussion are described in section III while conclusions are drawn in section IV.

II. The Proposed Model

This section is dedicated for details of proposed PV system. Our proposed system consists of five major modules: PV array model, DC-DC converter, MPPT controller, DC-AC inverter and synchronization module. Synchronization module comprises SVPWM, Phase Locked Loop (PLL) and voltage measurement sub modules. Block diagram of the proposed system is shown in Fig. 1. PV panel takes the solar irradiance and temperature as input and produces current and voltage. MPPT controller tracks the maximum power point of PV panel using P&O algorithm. DC-DC converter boosts up the output voltage and DC-AC inverter converts the DC output into AC. The synchronization module is used to synchronize the DC-AC inverter output with grid. PLL block generates a reference signal having same frequency and angle as that of the grid. SVPWM is a modulation technique that generates the controlled gating signals for the inverter [8].

A. Photovoltaic Array Modelling

A PV cell is a p-n semiconductor device that converts sunlight into DC current (electricity) using PV effect. Large number of PV cells are connected in series and parallel combination according to energy requirements. This arrangement is known as PV module. A PV array is defined as group of numerous PV modules connected in series (responsible to increase the array voltage) and parallel connections (responsible to increase current in the array) [11]. The equivalent circuit of a PV cell is a current source in parallel with an inverted diode, parallel or shunt resistor and a series resistor as shown in Fig. 2 [9].
Shunt resistor R_P characterizes leakage current of diode and series resistance R_S represents internal losses due to current flow. Performance of PV cells depend on two main factors i.e. temperature and irradiance. Following equations (1) to (4) represent the behaviour of PV device [12].

$$I = I_{PV} - I_D, \tag{1}$$

Where,

$$I_D = I_o[exp[\frac{q*v}{a*k*t}]-1] \tag{2}$$

So,

$$I = I_{PV} - I_o[exp[\frac{q*v}{a*k*t}]-1] \tag{3}$$

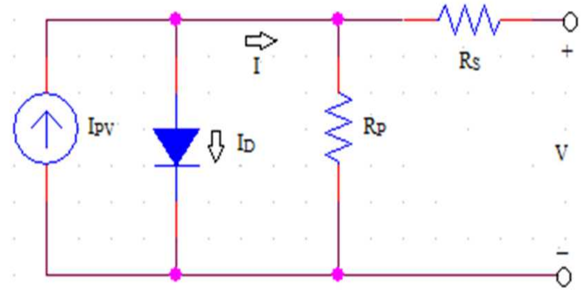

Fig. 2: Single Diode Model of a PV Device

$$I = I_{PV} - I_o[exp[\frac{V+Rs}{a*Vt}]] - \frac{V+1Rs}{Rp}. \tag{4}$$

Where,
I: Solar Cell Current (A)
I_{PV}: Current Generated by Incident Light (A)
I_D: Diode Current
q: Electron Charge
k: Boltzmann Constant
$T[K]$: Temperature of P-N Junction.
a: Diode Constant.
V_t: Thermal Voltage of Array.
R_S: Equivalent Series Resistance.
R_P: Equivalent Parallel Resistance.
I_O: Diode Saturation Current (A)
Complete system shown in Fig. 1 has been modelled in Simulink, MATLAB R2012a. Various modules of proposed PV system are discussed in subsequent sections. Block diagram of solar PV panel is shown in Fig. 3. Temperature and solar irradiation are the inputs of solar PV panel [9], [12]. In order to make the nature of PV panel generic, it is needed to create a mask of the module for user inputs. Mask created for this purpose is shown in Fig. 4. PV module depends on the following parameters:
N_s: Number of Cells in Series
N_{pp}: Number of Modules in Parallel
N_{ss}: Number of Modules in Series
a: 1.3977, Diode Constant
I_{scn}: Nominal Short-Circuit Voltage
K_p: Voltage Temperature Constant
K_i: Current Temperature Coefficient
V_{mp}: Voltage Maximum Power at STC
I_{mp}: Current at Maximum Power at STC
Mask shown in Fig. 4 depicts the parameters for BP MSX 120 array PV model, parameters are taken from its data sheet [13]. However, these parameters can be modified for any other PV panel. Some of the modules are explained in subsequent sections.

B. MPPT Control Algorithm

Power generated from a PV system primarily relies on weather conditions, for instance temperature and solar

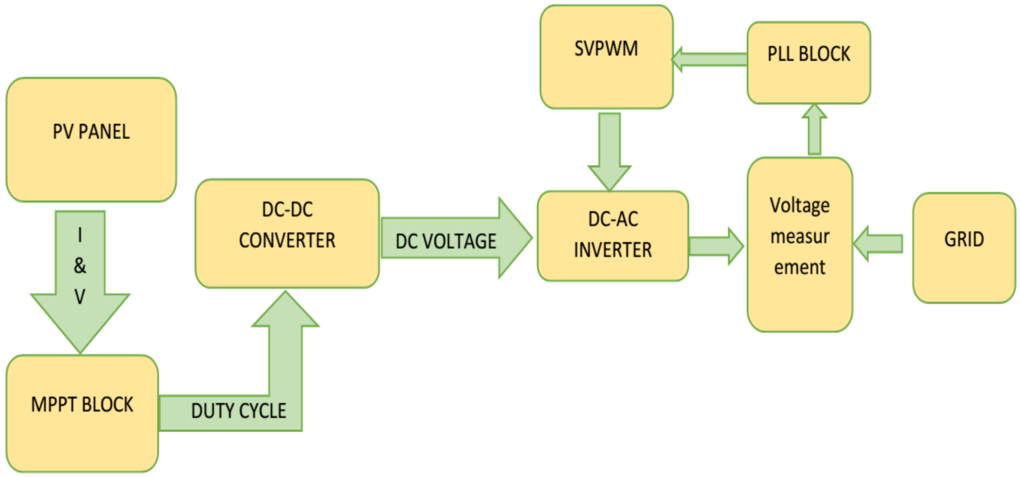

Fig. 1: Block Diagram of Solar PV System

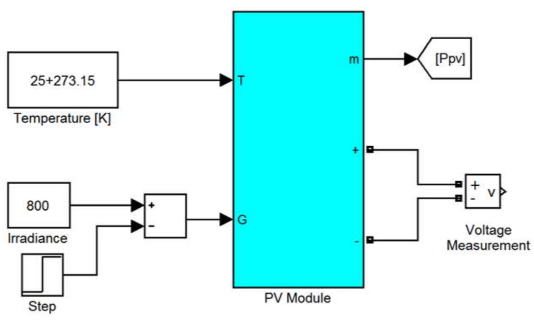

Fig. 3: Block Diagram of PV Module

irradiances. Low efficiency and high cost of a PV system demands that it must be operated at Maximum Power Point (MPP). The MPP of a PV system changes with atmospheric conditions or load variations. A typical solar panel converts only 30-40% of the incident solar irradiation into electrical energy [14]. A number of MPPT methods have been developed to enhance the efficiency of PV system. The PV model output characteristics are nonlinear with altered solar irradiance and temperature. Moreover, the solar irradiation is uncertain and it varies the MPP of PV module. Thus, a MPPT method is required to operate the PV module on its MPP. There are many techniques for MPPT, the most popular techniques are [15]: P&O, Fuzzy Logic Control, Incremental Conductance, Neural Network Control etc.

P&O is the most frequently used method because of implementation ease and low cost. It operates by adjusting the PV array operating voltage, and analysing the PV output power with the earlier one. The power

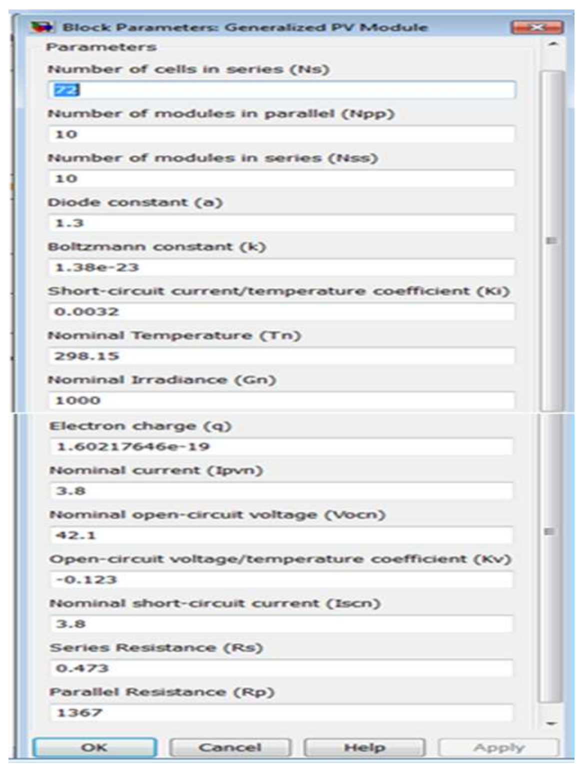

Fig. 4: Mask for Generalize PV Module

decreases (increases) with decrease (increase) in voltage when going on left of MPP. The power increases (decreases) with decrease (increase) in voltage when going on right of MPP. Consequently, if there is a rise in power, the successive perturbation must keep the same to acquire the MPP. Similarly, if there is a fall in power, the perturbation must be reversed. The P&O algorithm needs two measurements: the voltage (V_{pv}) and the current (I_{pv}) [9].

C. SVPWM Technique

Space Vector Modulation (SVM) is the modulation technique that was developed as vector approach to Pulse Width Modulation (PWM). It was developed to be used in three phase inverters. This technique generates Sine waveform having less harmonic distortion and produces high voltage. This quality makes it the best to use in power electronics. The main objective of any modulation approach is to get maximum variable output with minimum harmonics [16]. In context of SVM technique, consider a three phase half-bridge voltage source inverter [16], three voltages, each phase to centre-tap voltages can have only two possible values, namely $+V_{dc}/2$ or $-V_{dc}/2$, respectively. There are three switches corresponding to three phases, so at any time instant, inverter has eight possible states. If upper switch of the leg is on, it is indicated by the state 1. Similarly, if lower switch of a particular leg is on, it is indicated by state 0. As there are 3 legs, so there are 8 possible switching combinations. Line to neutral voltages can be found using the following three equations:

$$V_{an} = [2V_{ao} - V_{co} - V_{bo}]/3 \quad (5)$$

$$V_{bn} = [2V_{bo} - V_{ao} - V_{co}]/3 \quad (6)$$

$$V_{cn} = [2V_{co} - V_{ao} - V_{bo}]/3 \quad (7)$$

Summary of these states and line to neutral voltage applied accordingly is shown in Table I [16], [17].

So there are six active states of inverter and the rest two are zero states. The line to neutral voltages, i.e. V_{an}, V_{bn} and V_{cn}, are 120° apart. Two phase equivalent of the line to neutral voltages is written as follows.

$$V_{ref} = V_{ds} + jV_{qs} \quad (8)$$

By using Clark's transformation, the value of V_{ds} and V_{qs} is obtained. From equation (8), the magnitude and phase of the voltage V_{ref} can be determined. When plotting the magnitude and phase, the space vector magnitude and position corresponding to each switching state is determined as shown in Fig.5. Each of the vectors such as V100, V110 etc., shown in the diagram represents six voltage steps developed by inverter with zero voltages V000 and V111 located at origin. The inverter switches are in a steady state at each of these states. A switching pattern must be devised that produces a voltage which transitions in between these states and not only at the six vectors states, in order to develop a sine wave at the motor. This effectively produces a continuous rotating vector V_{ref}, which transitions smoothly from state to

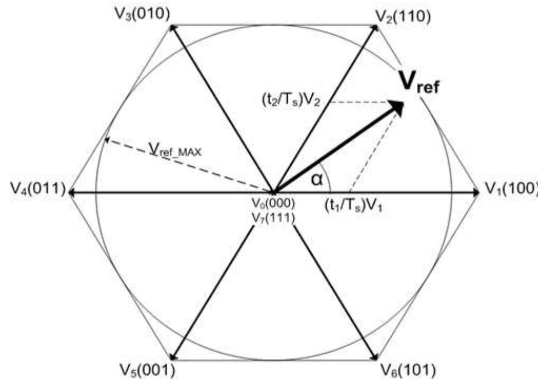

Fig. 5: Space Vector Corresponding to Each Switching States [16]

state.

A vector is produced that transitions smoothly between sectors using the appropriate PWM signals and hence provide sinusoidal line to line voltages which is equivalent to the input reference voltage. Thus, by using space vector modulation technique, the output voltages of the inverter are almost equal to the input reference voltages. The reference voltage is sampled at a particular frequency to obtain such output voltages. The output voltage will be closer to the reference voltage if the sampling frequency is greater but as the sampling frequency increase, the switching frequency also increases which further results in increased switching loss. So an optimum sampling frequency should be selected to overcome this problem. A formula must be derived to obtain the PWM time intervals for each sector. By sampling the reference voltages, the time for which active vectors are switched and sector in which these vectors are switched is obtained. The time and sector can be found from the magnitude and the position of reference voltages. The symbols T1 and T2, respectively represents the time periods for which the active vector along the lagging edge and the leading edge are switched for the understanding of the reference voltage space vector in a given sampling time period. Ts is the symbol that represents the sampling time period. The time T1 and T2 can be obtained, by applying volt-sec balance in vector form. The volt-sec balance along ds and qs axis is written as following from equation (8):

$$V_{ref} * T_s * cos(\alpha) = [(V1 * T1 * cos(0)) + (V2 * T2 * cos(60))] \quad (9)$$

$$V_{ref} * T_s * sin(\alpha) = [(V1 * T1 * sin(0)) + (V2 * T2 * sin(60))] \quad (10)$$

Where, *Vs* is the magnitude of the reference voltage and *V1* & *V2* are the magnitude of the sector voltages that is equal to DC link voltage, Vdc. The α is the position of

TABLE I: Inverter Switching States

States	ON Switches	Van	Vbn	Vcn	Space Voltage Vectors
0	462	0	0	0	V0(000)
1	162	2(VDC/3)	-(VDC/3)	-(VDC/3)	V1(100)
2	132	(VDC/3)	(VDC/3)	-2(VDC/3)	V2(110)
3	432	-(VDC/3)	2(VDC/3)	-(VDC/3)	V3(010)
4	435	-2(VDC/3)	(VDC/3)	(VDC/3)	V4(011)
5	465	-(VDC/3)	-(VDC/3)	2(VDC/3)	V5(001)
6	165	(VDC/3)	-2(VDC/3)	(VDC/3)	V6(101)
7	135	0	0	0	V7(111)

reference vector w.r.t the beginning of sector where the reference vector's tip lies. Rearragning equations 8 and 9, the switching time T1 and T2 is found and is stated as:

$$T1 = \{[Vs * Ts * sin(60 - \alpha)]/(Vdc * sin(60))\} \quad (11)$$

$$T2 = \{[Vs * Ts * sin\alpha]/(Vdc * sin(60))\} \quad (12)$$

The sampling time is as follows:

$$T_s = (T1 + T2 + T0) \quad (13)$$

In equation (13), T0 is the time for which the null vectors (0 and 7) are switched on.

D. Inverter Connected to Grid

For grid connected system it is important to synchronize the inverter's voltage and frequency with the grid. For this purpose, synchronization between inverter and the grid has been done via feedback system. Builtin SIMULINK PLL block has been used. The purpose of PLL block is to generate grid's frequency, voltages and phase angle which is then fed into SVPWM block. SVPWM block generates signal for inverter hence the output is synchronized with grid. SVPWM block has been designed on the basis of model presented in [16]. The inputs of this block are the output from PLL block and current from the inverter. It generates the switching signal that is again fed to the inverter. This is how this model for feedback system is working in grid connected mode. Simulations of PV array with boost converter and synchronization of inverter with grid have been performed. Any type of PV array can be used in the proposed system by assigning its parameters in the mask shown in Fig. 4. The BP MSX 120 PV model is used for simulation. The temperature, irradiance and load are varied to determine the capability of MPPT to track the MPP under abrupt change of weather conditions and variable load.

E. Results and Discussion

The characteristics of BP MSX 120 at STC 25°C are briefed in Table II [13]. The BP MSX 120 modules are connected in series and parallel to make a PV array. A PV array of 12 KW is made by connecting 10 modules in series and 10 modules in parallel. The characteristics of this array have already been depicted in Fig. 4.

TABLE II: BP MSX 120 Parameters Values

BP MSX 120	
Short Circuit Current	3.56 A
Current at maximum power point	3.87 A
Voltage at maximum power point	33.7 V
Open Circuit Voltage	42.1 V
Number of cells in series	72

1) The Characteristics of PV Array with Varying Temperature and Irradiance: The current-voltage (I-V) and power-voltage (P-V) characteristics of PV array as a function of temperature and solar irradiance are shown in Figs. 6 and 7. These curves are nonlinear and significantly depend on the temperature and solar irradiation. The I-V & P-V characteristic curves of PV array for different values of solar irradiance are shown in Fig. 6. It can be seen that as the irradiation rises, the current rises more than the voltage and the MPP increases as well. Fig. 7 explains the P-V & I-V characteristic curves of PV array at different temperatures. It can be observed that the increase in temperature results in decreasing the power and voltage of PV array while the current remains almost constant. Therefore, temperature does not affect the current.

III. Conclusions

In this paper, we have presented a generalized PV system with MPPT controller, DC-DC converter, inverter and synchronization module. Resistive load has been used for simulation studies. The proposed system has been simulated in Matlab/Simulink. First, the generalized PV module is designed for which the parameters provided in the mask can be modified to use any type of PV module. The simulations of PV array BP MSX 120 array showed that the simulated model is accurate because the current voltage characteristics are same as

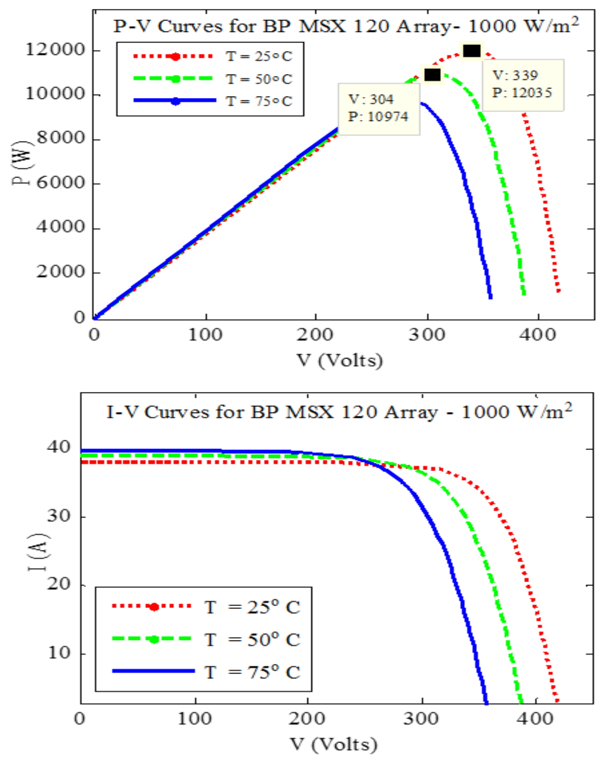

Fig. 6: BP MSX 120 Array Characteristic Curves as a Function of Solar Irradiance (G)

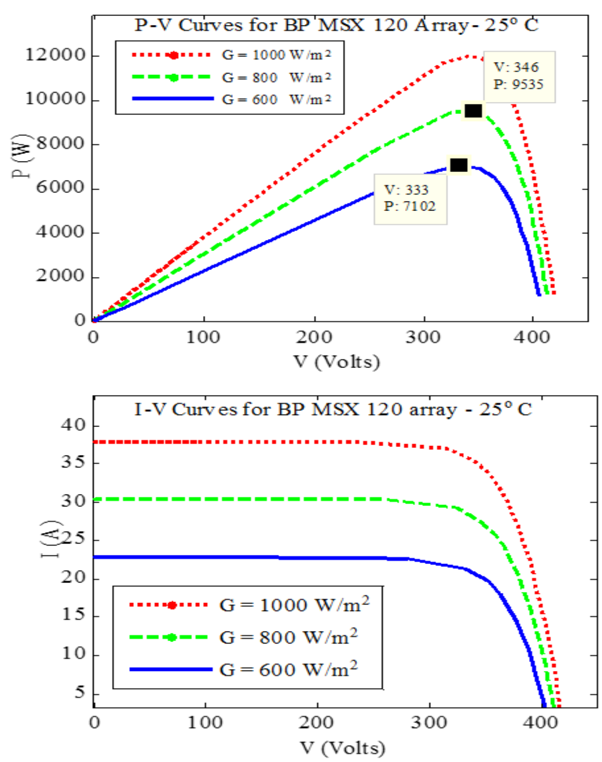

Fig. 7: BP MSX 120 Array Characteristic Curves as a Function of Temperature (T)

given in the data sheet. Then the same PV array with boost converter is analysed under the abrupt change of irradiance, temperature and variable resistive load. The simulation results show that PV output power, voltage and current vary with the changes of temperature and irradiance. The change in load does not affect the output of photovoltaic array. The simulation results also show that P&O based MPPT algorithm can track the MPP of the PV under different weather conditions. The proposed model has been successfully synchronized with grid.

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