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ADAPTIVE CONTROL IMPLEMENTATION FOR THREE PHASE THREE LEG FOUR WIRE SAPF ON DSPACE 1103 DSP BOARD

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Abstract: The aim of this paper is the implementation and validation of the optimal control of four–wire, shunt active power filters, designed for industrial use. The validation had been done by simulation at first, on the complete virtual model of the active filtering system, and finally on the experimental setup. The latter consists of the active power filter controlled by means of a dSPACE DS1103 prototyping board, tested in a real industrial environment. This environment is characterized by high load variation both regarding the harmonic content of the currents on the three phases as well as the phase load balance. This leads to a difficult imbalance current compensation for the three–wire active filters, difficulty which is overcome by the four–wire active filters. At the same time, high harmonic (and reactive) current imposes high compensating capacitor working voltage. The variable harmonic content of the load current, makes unpractical to maintain a high capacitor voltage, so the adaptive control reduces the switching power loss without affecting the compensation performance. The performance of the control algorithm was quantitatively proved by analyzing the data sampled by the prototyping board analog to digital converters in the Matlab Simulink environment.

Keywords: DSP implementation, Power Electronics Applications in Power Systems and Utilities, Harmonics and Active Filtering

1. INTRODUCTION

The active power filter power section and control scheme is illustrated in Figure 1. The nonlinear load consists of the power electronics department of a company from Craiova and it includes a whole range of equipment, active, reactive and nonlinear (such as electric motors, heating resistors, fluorescent lighting tubes, air conditioners, etc.). Therefore, if the virtual validation of the control algorithm was done for a known load, for the case of the experimental validation, the load could be controlled during the experiments, as it was dependent on the activity of the industrial facility at the experiment time.
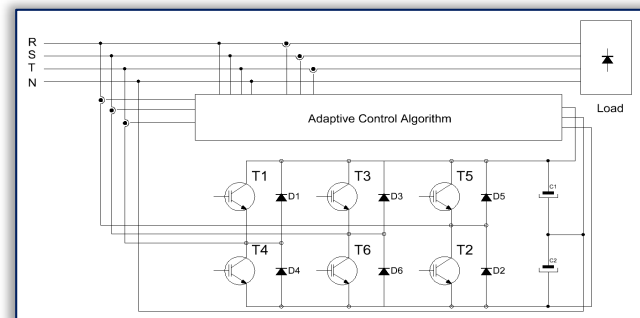

Figure 1. Three phase four wire active filtering system

2. THE ADAPTIVE CONTROL OF THE COMPENSATING CAPACITOR VOLTAGE

The control algorithm is based on the indirect current control [6][13–14] and it contains the main sections:

≡ The compensating power computing section.
≡ The power grid current controller (hysteresis);
≡ The compensating capacitor voltage controller (proportional–integrative).

The voltage controller imposed voltage value and controller parameters (proportionality constant and integration time constant) are adapted as a function of the load magnitude. This is because the non–active power to be compensated is dependent on the load and maintaining the capacitor voltage at a fixed value leads to lower energetic performance of the active compensator or to lower compensating performances. The dependence between the capacitor voltage value for the power to be compensated is [16]:

$$V_{DC} = V_{DCN}\sqrt{\frac{S_F}{S_{FN}}}$$ (1)

where:

≡ V_{DC} – the compensating capacitor voltage;
≡ V_{DCN} – the nominal compensating capacitor voltage, given for the nominal apparent power;
≡ S_F – the apparent power to be compensated;

$$S_F = \sqrt{S^2 - P^2}$$ (2)

≡ S_{FN} – the nominal apparent power to be compensated.

The voltage controller was tuned using the modulus optimum criterion, for the closed loop unity feedback system [15]. The proportionality constant and the time integration constant are dependent on the average value of the capacitor voltage:

$$K_{pv} = K_1 V_{DC}; \quad T_{iv} = \frac{K_2}{V_{DC}} \tag{3}$$

where: K_1 and K_2 depends on the parameters of the control system (the compensating capacitance, the power grid voltage, the voltage transducer and the pass–band frequency of the unity feedback system) [16].

3. THE VIRTUAL IMPLEMENTATION AND VALIDATION OF THE ADAPTIVE COMPENSATING CAPACITOR VOLTAGE CONTROL SYSTEM

The control algorithm was firstly implemented and validated on the complete virtual model of the considered active filtering system, built in Matlab Simulink (Figure 2). It can be seen that all the necessary computations had been grouped in a subsystem (Control_alg), detailed in Figure 3.
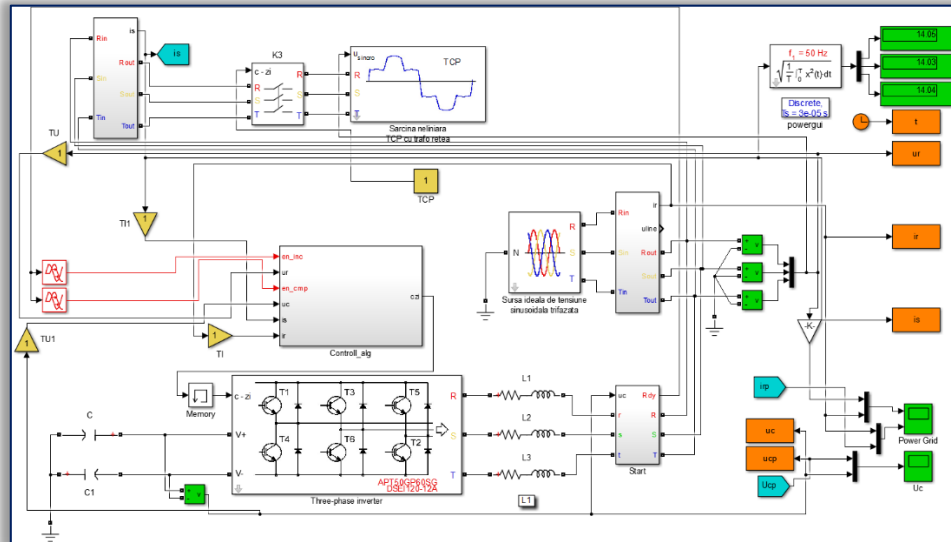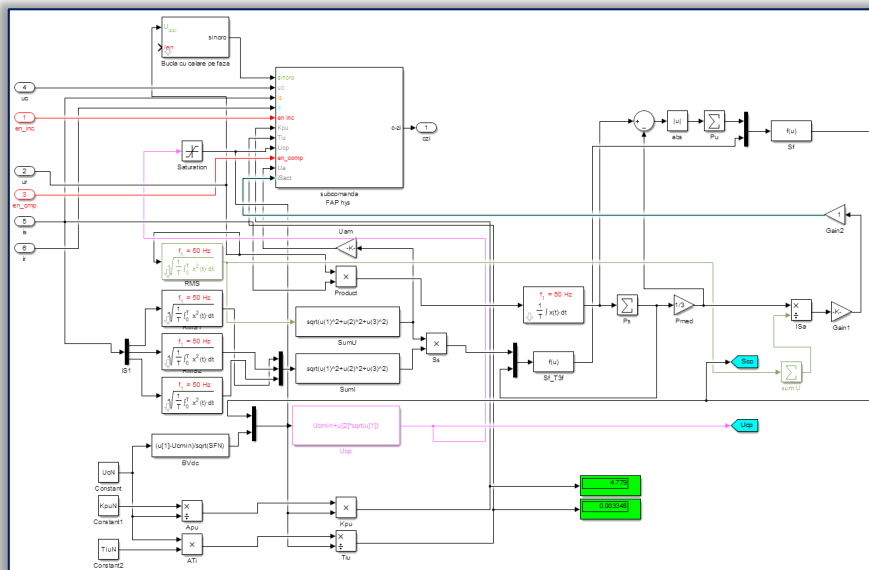

Figure 2. Virtual active filtering system

Figure 3. The active power filter control algorithm subsystem of the virtual model

The control systems of the active filter had again been grouped to a subsystem which includes three sections (Figure 4):

≡ The compensating capacitor voltage control loop; it receives at its input three signals: the capacitor imposed voltage, the voltage controller proportionality constant and the voltage controller integration constant (Figure 5).

≡ The power grid current control loop (Figure 6);

≡ Auxiliary subsystems for the active filtering system initialization and protection against hazardous situations (Figure 5).

The current imposed to the current control loop has two components [5–6][13][16]:

≡ the compensating capacitor charging current and the power inverter loss covering current;

≡ the load active current computed outside the control subsystem, applied at the subsystem input.

The instantaneous values for the compensating capacitor voltage and voltage controller parameters are also computed outside the control subsystem and applied to the voltage loop by means of dedicated input ports (Figure 3, Figure 4).

Figure 4. The active power filter control susbsystem

The computation of the optimal capacitor voltage, as well as the corresponding voltage controller parameters is done by a dedicated section of the model in Figure 3.

It can be seen that the compensating power S_f is computed as function of the balanced grid voltage RMS values, balanced load current RMS values and load active power. The compensating power gives the optimal capacitor voltage, which further, gives the voltage controller parameters [16]. The phase locked loop, necessary for the grid voltage template is also located in the root of the control model [3][5].
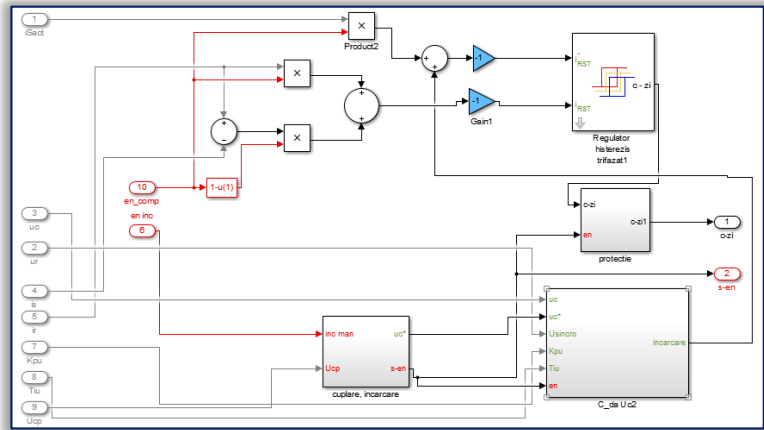

a)   b)
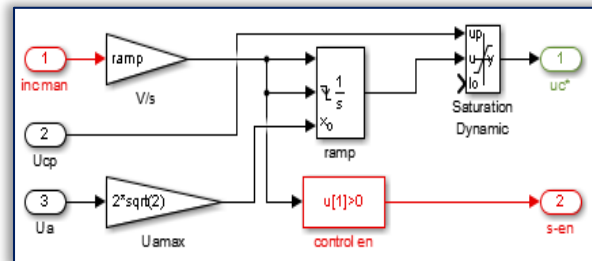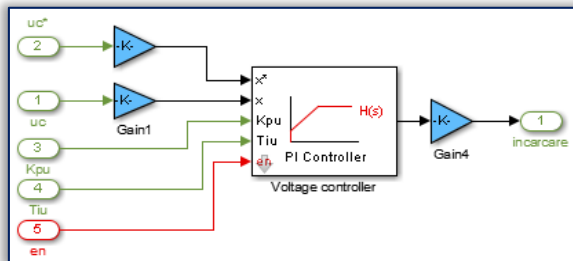
Figure 5. Detail of: a) compensating capacitor voltage control loop subsystem, b) start–up process control subsystem

The load balanced current amplitude, which is a component of the control system imposed current, is computed also in the root of the control model and applied at the input of the control subsystem [6][16].

The rated parameters of the virtual active compensator correspond to the rated parameters of the experimental system, located at the plant.

However, the virtual nonlinear load was a typical load corresponding to a drive system with thyristor rectifier, unlike the real load which cannot be controlled.

The current absorbed by the nonlinear load is illustrated in Figure 3. The total harmonic distortion factor of this current is 27.77%, for a RMS value of 14.74 A.

The apparent power of the load is 9.73 KVA, giving a compensating power of 9.09 kVA (for an active power of 3.46 kW. Therefore, the adapted parameters of the compensating capacitor voltage regulation system are:

≡ $V_{DC}^* = 827.04$ V;

≡ $K_{pv} = 4.779$;

≡ $T_{iu} = 3.348 \cdot 10{-3}$.

The compensated current is illustrated in *Figure 8*. The total harmonic distortion factor of this current is 7.16%, giving a filtering efficiency of 3.74. Because the power grid apparent power decreases to 4.78 kVA (for a total active power absorbed from the power grid by the active filtering system of 4.76 kW) the power factor increases after the compensation from 0.355 to 0.996. The stated results had been obtained for a simulation time step of 3 μs.
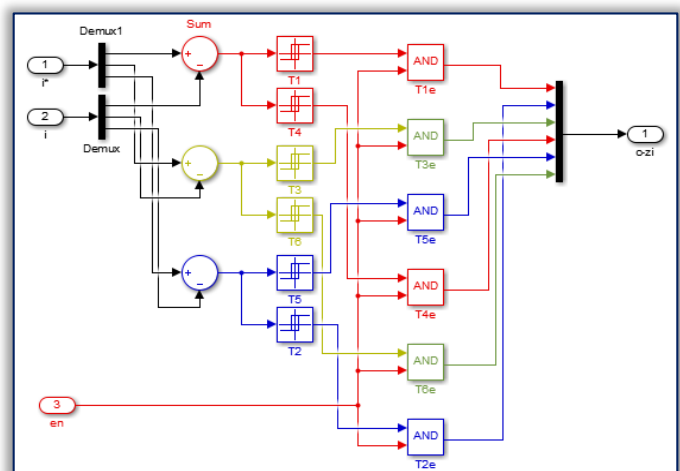

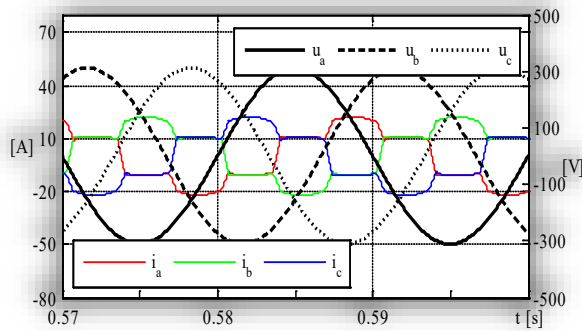Figure 6. The hysteresis current controller

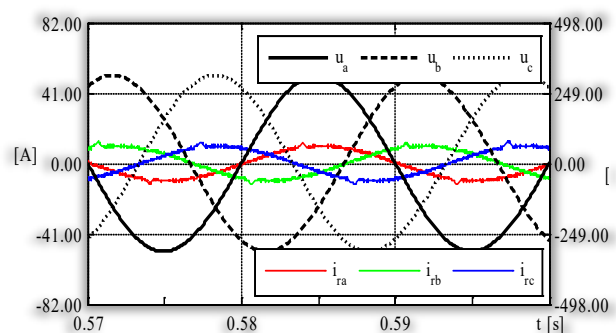Figure 7. The current absorbed by the nonlinear load

Figure 8. The compensated current

4. THE EXPERIMENTAL IMPLEMENTATION AND VALIDATION OF THE ADAPTIVE COMPENSATING CAPACITOR VOLTAGE CONTROL

The implementation of the control algorithm for the dSPACE DS1103 prototyping board was done in the Matlab Simulink environment, by exporting the control section of the virtual active compensator in Figure 2. The resulting Simulink model, illustrated in Figure 3, was compiled and loaded to the DS1103 board program memory. In the preparation process, the former virtual power section with its voltage and measurement blocks was replaced by the prototyping board links to the experimental power section [15].

The link between the power section and the control system of the experimental active filtering system is done by the prototyping board analog to digital converters, at the input side. Thus, the low voltage signals from the power section transducers are applied to the prototyping board, converted to digital signals, and further, to Simulink signals. The later are available in the model at the output of the Real Time Interface block attached to each analog to digital converter (Figure 9) [10–11]. The Simulink signals received from the transducers are multiplied with the corresponding measurement constants (the yellow Gain blocks in Figure 9). The value of these constants depend on each transducer measurement ratio (considering the prototyping board rated analog input of (±10 V) [10].
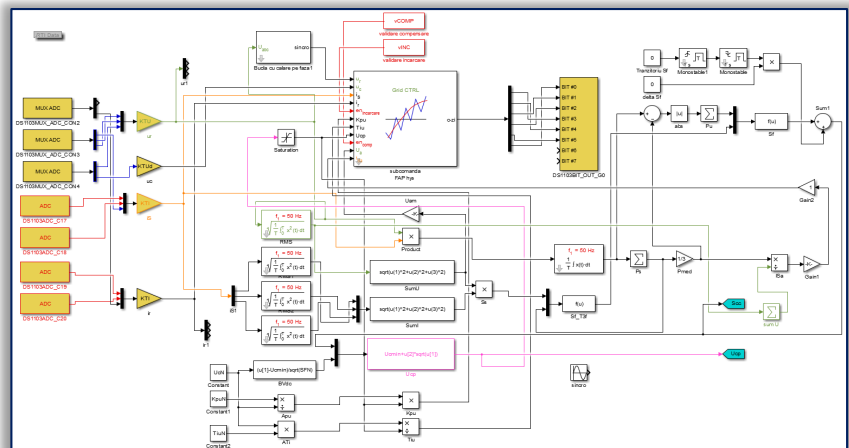

Figure 9. Experimental three phase four wire active filter control model

The real time control is done by controlling the values of some Simulink signals/parameters by means of a specialized control panel built in ControlDesk NG (the dSPACE board specific software) [9].

The real time control of the experimental active filter is assured by dedicated Simulink signals. Their role is to control the startup process of the active filter and to control the working status (Figure 9):

≡ Filter initialization – is controlled by the signal generated by the Constant block, Start, or in other words, by the value of the Matlab variable vINC;

≡ Compensation status – the compensation can be activated manually after the initialization of the active filter (to avoid high startup currents, although the startup process can be done with full load) by the signal generated by the Constant block, comp (the value of variable vCOMP) – Figure 9:
  o this signal applies to the current controller all the active current to be absorbed from the power grid by the active filtering system, or just the active component necessary to the active filter to function (idle state);
  o It also controls the feedback current components, in accordance to the selected objective (idle or working state).

The real time control of the experimental active filtering system is done by means of a virtual control panel, built in Control Desk NG, the application software for the DS1103.

The virtual instruments in the control panel are linked to the Simulink control model, more precisely to the model blocks. The virtual instruments can be linked to Simulink signals (available at the blocks output ports) or block mask parameters (such as the constant output value of a *Constant* block, defined as a mask parameter). Therefore, depending on the virtual instrument type, there are [9]:

≡ Read connections – the panel meters, control lamps, numeric displays and oscilloscopes (time arrays) are used to monitor the experimental equipment status or for qualitatively and quantitatively real time studies;
  o The instruments are displaying in real time the linked signal instantaneous value;
  o The oscillographed signals may be saved in a Matlab mat file, for offline analysis;
  o Besides the oscillographed signals, any signals or parameters from the control model can be added to the saved file;

≡ Read/write connections – the numeric input instruments read and display the block parameter they are linked to, but also can modify its value;

≡ Write connections – the push button placed on the control panel are attached to block parameters and write its value according to the button configuration.

The correct implementation of the control algorithm was tested at the plant site, for the normal working environment. At the experiment

Figure 10. The experimental active filter control panel built in Control Desk NG

time, an important current imbalance was observed, as well as very different current harmonic distortion between the power grid phases. The active power filter was mounted at the power transformer output connections so the consumers are from a large variety of types (fluorescent lamps, switched mode power supplies, motor drive rectifiers and induction motors). The analyzed signals were sampled with the DS1103 prototyping board acquisition system [8].

The current absorbed by the industrial consumers is illustrated in Figure 11. The current RMS values and total harmonic distortion factors are synthetized in Table I. It can be seen both qualitatively and quantitatively that the current is distorted as well as imbalanced.

The current absorbed from the power transformer, after the compensation, is illustrated in Figure 12. Qualitatively, it results that the compensated current is almost sinusoidal, considering the harmonic content due to the active filter switching operation. Quantitatively, though, it results that the compensated current has a high harmonic content, the total harmonic distortion factor being higher than for the load current. On the other hand, the current imbalance is greatly reduced.
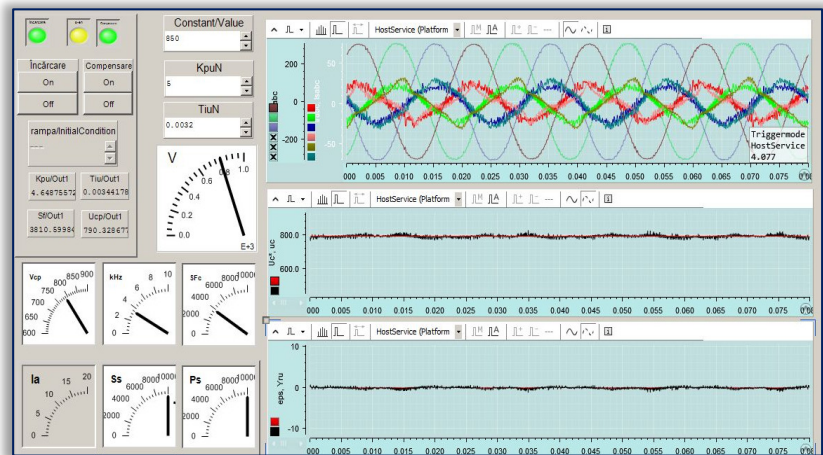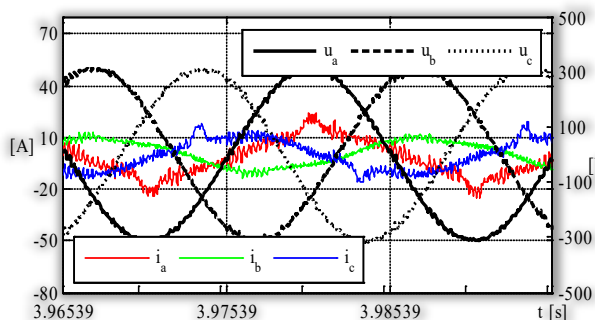

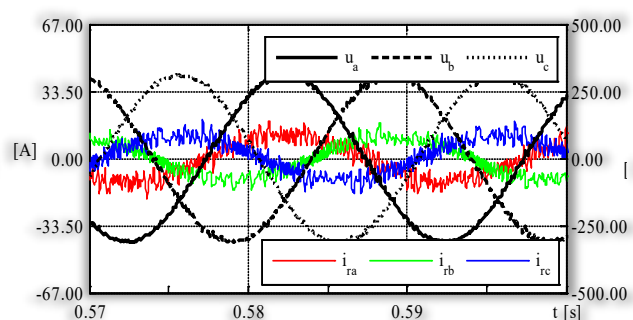Figure 11. The current absorbed from the power grid by the nonlinear load

Figure 12. The compensated current absorbed from the power grid by the active filtering system

The high current distortion is due to the relatively low value of the interface filter inductance, corroborated with the prototyping board time step of 30 µs.

This leads to the conclusion that the control section of the experimental active power filter is working properly, but improvements need to be made in the power section, especially regarding the inductive interface filter.

The instantaneous parameters of the voltage controller (proportionality constant and integration time constant) as well as the compensating capacitor imposed voltage on 2 s time span as a function of the compensating power is:

≡ PL ∈ [5010.7, 5283.2] W;

≡ SF ∈ [2950.9, 3260.8] VA;

≡ Kpu ∈ [4.2058, 4.4497];

≡ Tiu ∈ [0.0036, 0.0038];

≡ u*c ∈ [704.05, 744.88];

It must be noted that because the nonlinear load is not a controlled laboratory load (keeping its parameters stable in time) some discrepancies are inherent between the data sampled with the DS1103, the data captured with the Metrix oscilloscope, or the screen capture of the virtual control panel. This is because the captures cannot be done at the same time, but at a difference of several minutes one compared to the next, while the consumer being very dynamic.

Figure 1. Numerical results

Current RMS values					
I_{La} [A]	I_{Lb} [A]	I_{Lc} [A]	I_{Sa} [A]	I_{Sb} [A]	I_{Sc} [A]
10.79	6.92	8.74	9.41	8.40	8.78
Current total harmonic distortion factors					
THD_{iLa} [%]	THD_{iLb} [%]	THD_{iLc} [%]	THD_{iSa} [%]	THD_{iSb} [%]	THD_{iSc} [%]
30.21	17.03	27.91	36.24	27.35	32.33

Note: This paper was presented at CNAE 2022 – XXth National Conference of Electric Drives, organized by University POLITEHNICA Timisoara, Faculty of Faculty of Electrotechnics and Electroenergetics (ROMANIA), in Timisoara, ROMANIA, in 12-13 May, 2022.

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