The Method Makes Use of Vector Currents, Voltages and Magnetic Variables and Reflects the Physical Phenomena Occurring in the Machines

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Abstract*- The development of an equivalent circuit for a phase winding of a three-phase stator consisting of scalar electrical, vector electrical and vector magnetic sections facilitated the referral of scalar electrical voltages to the vector electrical section of the equivalent circuit due to the equality of scalar and vector current magnitudes. This resulted in voltages and current coexisting with magnetic variables on the magnetic axis of the phase winding, thereby showing that electrical variables can be presented as vector quantities on the magnetic axis of the phase winding. The vector electrical section of the equivalent circuit connected the scalar electrical section to the vector magnetic section, resulting in a single circuit for analysis of the electromagnetic system. The energization of all three windings of the three-phase stator by three-phase voltages produced resultant current, voltage, and magnetic vectors associated with a phase winding and a single vector voltage equation for all three windings. The absence of this single equivalent electrical circuit of the electromagnetic system and the results derived from it has not inhibited growth in the area of transient analysis and modeling of electrical machines, however, its introduction reveals the background of the various phenomena occurring in the machine and shows the development of current and voltage vectors in the electromagnetic system.

Keywords*- *Modeling, Machine, Electrical, Phase, Two-pole

I. INTRODUCTION

Vector analysis is widely used for the analysis, modeling and control of electrical machines. The method makes use of vector currents, voltages and magnetic variables and reflects the physical phenomena occurring in the machines. The application of the vector method to the modeling, analysis and control of electrical machines has many advantages over other methods, some of which are: a reduction in system equations, easier machine control, a clear conceptualization of machine dynamics and easier analytical solution of dynamic transients of machine variables [1]. However, the material presented by Kovacs [2]for the vector analysis of a three-phase stator requires an equivalent circuit to demonstrate the generation of vector currents and the production of vector voltages to clearly formulate the vector method.

This paper presents the development of an equivalent circuit for an electromagnetic system consisting of scalar electrical, vector electrical and vector magnetic sections and shows the production of a vector current from its scalar counterpart that leads to the production of vector voltages on the magnetic axis of the system. A single voltage equation is also developed to represent all three windings of the three-phase stator.

II. RELATED WORK

Vector analysis of electrical machines was developed by Kovacs and Racz[3] and is widely used in the modeling, transient analysis and control of these machines. The vector method has been documented in many books of reputed authors [4-7]and has been employed by Holtz [8-10] in the development of vector equations for electrical machines. However, the above application of the vector method in the analysis of electrical machines utilised vector currents, voltages and magnetic variables but did not represent them in an equivalent circuit of the machine.

III. EQUIVALENT CIRCUIT OF A PHASE WINDING OF A THREE-PHASE MOTOR STATOR

A cross section of the stator windings of a two-pole, three-phase machine is shown in Fig. 1. The phase windings are shown to be displaced from each other by 120^0 and the positive direction of current flowing through each winding is upwards through the non-primed side and downwards through the primed side. Using this convention of current flow through the windings, positive magnetic axes were developed for each phase winding, along which all magnetic quantities exists.

The analysis of electromagnetic systems has traditionally been performed with the production of two circuits, a scalar electrical circuit for electrical analysis and a vector magnetic circuit for magnetic analysis [11] as shown in Fig. 2, where V_a represents supply voltage,i_a winding current, R_a resistance of winding aa', $L_a$self inductance of winding aa',$\mathcal{R}_a$the reluctance, N_a number of turns in winding aa', and flux$\phi_a$produced by winding aa'.

However, quantities in the electrical circuit affect quantities in the magnetic circuit and vice versa. As a result of the dependence of both electrical and magnetic variables on each other, the development of an equivalent circuit containing both electrical and magnetic quantities would prove to be very useful in the analysis of electromagnetic systems. Since the three-phase stator is an electromagnetic system, then the development of an equivalent circuit containing both electrical and magnetic quantities would be a powerful tool in the vector analysis approach of this electromagnetic system.

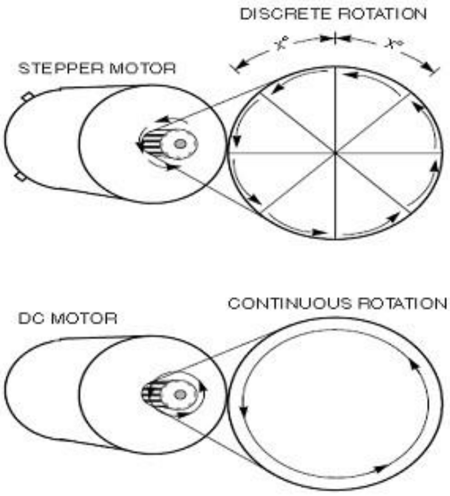


Figure 1. Traditional Electrical and MagneticEquivalent Circuits of Phase Winding aa' of The Three-Phase Stator

For this analysis, one phase winding of the three-phase stator, winding *aa′* was initially selected for analysis. This winding is represented in Fig. 3(a) by its center conductors and the current$i_a$through the winding is in the positive direction. Fig. 3(a) is divided into two sections: electrical quantities are presented in the Scalar Electrical section and the other section containing the winding with its electricalscalarcurrent$i_a$and magnetic variables, magnetic

Field intensityH_a, flux density B_a, flux ϕ_a, flux linkage λ_a and current vector $\mathbf{i}_a$all on the positive (+ ve) magnetic axis of winding *aa′*. The electrical scalar current i_a, which leaves the Scalar Electrical section of the circuit flows through the winding and produces vector magnetic field intensity$H_a$along the positive magnetic axis of winding *aa′*. This vector magnetic field intensity$H_a$must be produced by a current vector $\mathbf{i}_a$ on the positive magnetic axis of winding *aa′*, hence, it can be said that the electrical scalar current $i_a$on passing through winding *aa′* produces current vector $\mathbf{i}_a$ on its positive magnetic axis.

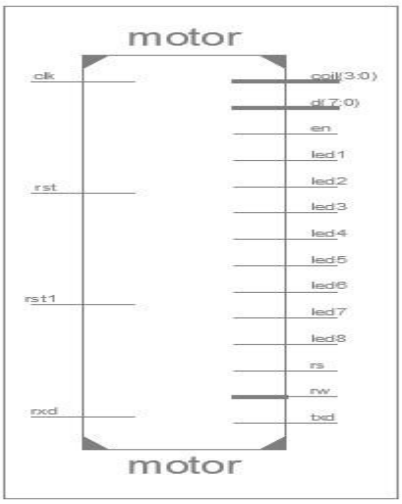


Figure. 2: RTL schematic

Fig. 3(b) consists of three sections: magnetic processes beginning and ending with current vector $\mathbf{i}_a$, a Scalar Electrical section as described earlier and a Vector Electrical section containing current vector $\mathbf{i}_a$separating the above two sections. The vector electric current $\mathbf{i}_a$, on entering the Scalar Electrical section, produces a scalar current i_a in the Scalar Electrical section, and the scalar electrical current $i_a$on entering the Vector Electrical section, produces a vector electric current $\mathbf{i}_a$ on the magnetic axis of winding *aa′* as shown in Fig. 3(b). Hence the magnetic axis of winding *aa′* completes the circuit making i_a and $|\mathbf{i}_a|$ of equal magnitudes.

The equivalent circuit of the three-phase stator with phase winding *aa′* energized is obtained by replacing the Magnetic Processes of Fig. 3(b) with current transformer CT and reluctance $\mathcal{R}_a$. as shown in Fig. 3(c). The turns ratio of current transformer CT is 1:$N_a$and$\mathcal{R}_a$is the reluctance to flux ϕ_a. The complete equivalent circuit of the three-phase stator with phase winding *aa′* energized as shown in Fig. 3(c) consists of three sections: the Scalar Electrical section, the Vector Electrical section and the Vector Magnetic section. The current vector$\mathbf{i}_a$exists on the positive (+ ve) magnetic axis of winding *aa′* in the Vector Electrical section of the circuit, and the current transformer CT produces the magnetomotiveforce (mmf) $N_a\mathbf{i}_a$in the Vector Magnetic section that drives the flux$\phi_a$through the magnetic circuit reluctance$\mathcal{R}_a$.

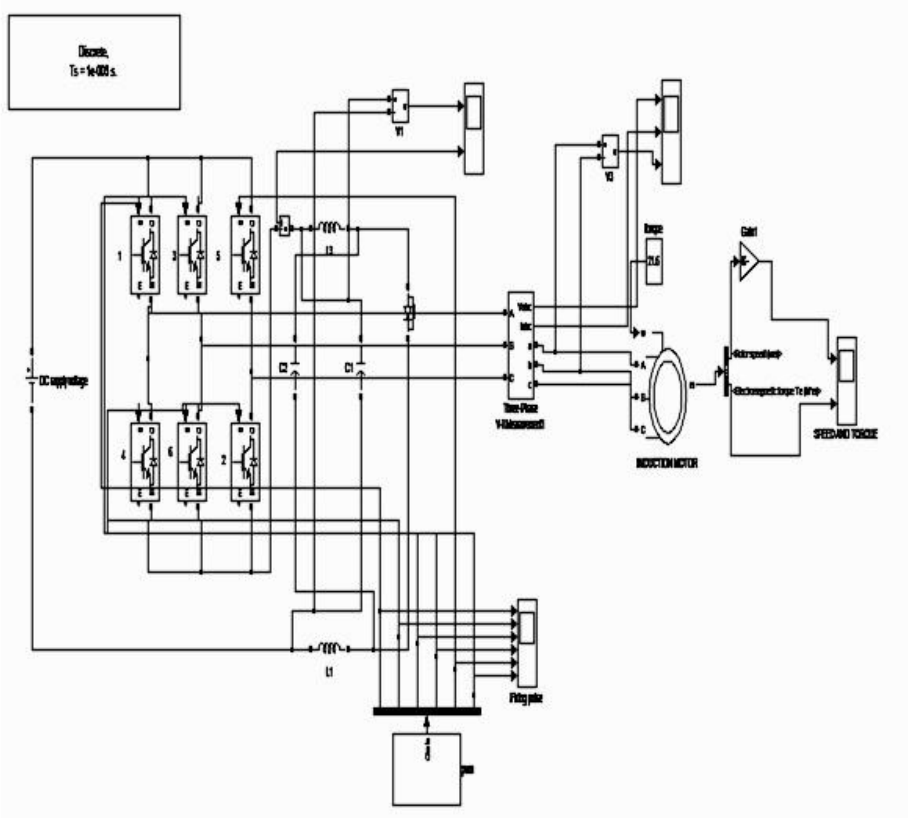
The voltage equation in the Scalar Electrical section is given by:

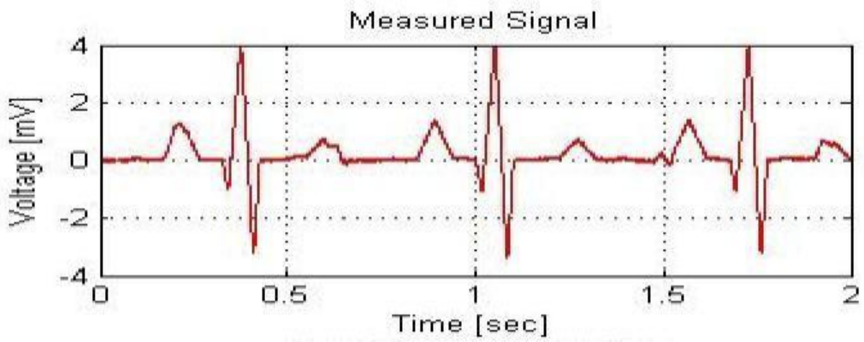
$$V_a = i_a R_a + L_a \frac{di_a}{dt} \qquad (1)$$

The voltages in the Scalar Electrical section of Fig. 3 (c) can be referred to the Vector Electrical section of the circuit since$i_a = |\mathbf{i}_a|$ resulting in:

$$\mathbf{W}_{k+1} = \mathbf{W}_k + 2\,\mu\,\varepsilon_k \mathbf{X}_k \qquad (2)$$

and producing the equivalent circuit of Fig. 4, with all voltages residing on the positive (+ ve) magnetic axis of winding *aa′*. Therefore the equivalent circuit of the three-phase stator with phase winding *aa′* energized has been represented by Vector Electrical and Vector Magnetic sections with current vector, voltage vectors and magnetic variables all existing on the positive (+ ve) magnetic axis of winding *aa′*.





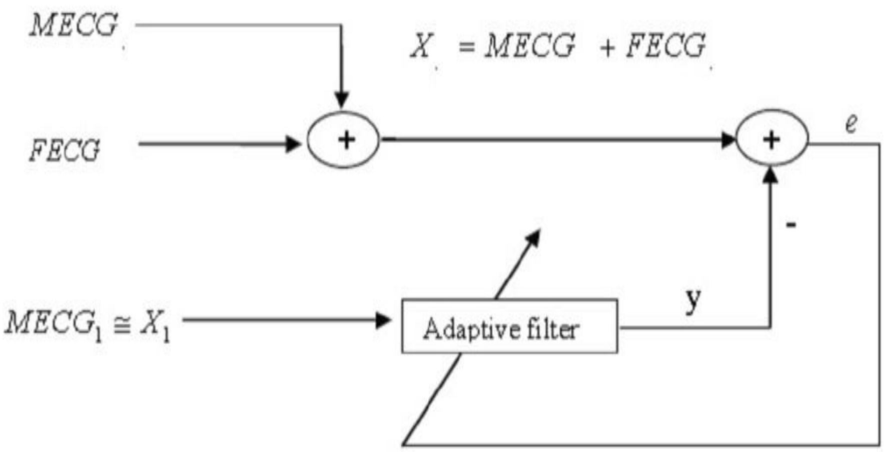


Figure 3. Equivalent Circuit of Three-Phase Stator with Winding aa' Energized(a) Scalar Electrical and Scalar Electrical, Vector Electrical & Magnetic Sections (b) Scalar Electrical, Vector Electrical Sections and Magnetic Processes (c) Scalar Electrical, Vector Electrical and Vector Magnetic Sections [12, 13]

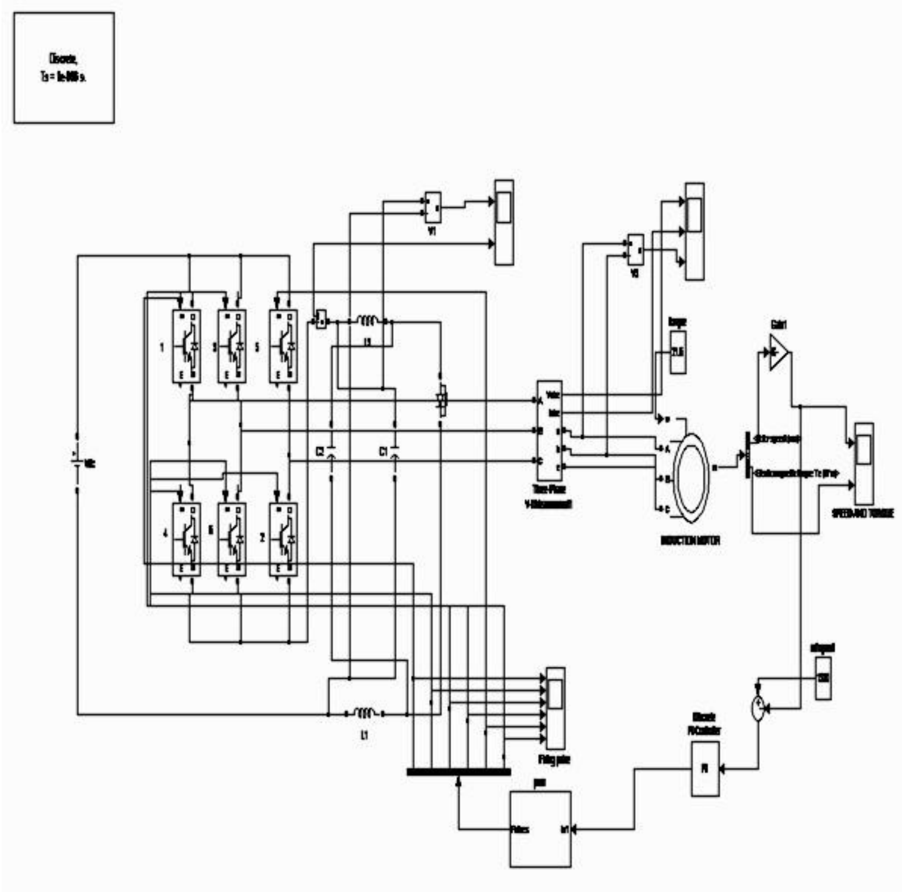


Figure 4. Equivalent Circuit of Three-Phase Stator with Winding aa' Energized with Vector Electrical and Vector Magnetic Sections

IV. RESULTANT CURRENT VECTOR

If the phase windings *aa'*, *bb'*, and *cc'* of Fig. 1 are energized with currents i_a, $i_b$and$i_c$respectively, then using the equivalent circuit developed in Fig. 3(c), current vectors i_a, i_b and i_c would be respectively produced on magnetic axes *aa'*, *bb'*, and *cc'* as shown in Fig. 5. These three current vectors i_a, i_b and i_c can be vectorially summed resulting in the resultant current vector i_{res}[10],

$$s(t) = V\cos(2\pi fct). \qquad (3)$$

whereaanda^{2}are unit vectors representing the position of the positive magnetic axes of windings *bb'* and *cc'* respectively and:

$$\vec{a} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}, \quad \vec{a}^2 = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \qquad (4)$$

If the three-phase stator is energized with three-phase currents of instantaneous values given by:

$$i_a = Imc^{os}(wt-90^{o)}$$
$$i_b = Imc^{os}(wt-120^{o})(5)$$
$$i_c = Imc^{os}(wt-240^{o})$$

then, the resultant current vector is obtained by substituting Eq(5) into Eq(3) [10] and given by:

$$B_i+1 = \alpha I_i + (1-\alpha).B_i \qquad (6)$$

and the resultant current vector associated with phase windings is given by, where:

$$G = \partial G + G (7)$$

Resolving $i_p$along each magnetic axis yields the instantaneous values of phase current in Eq(5) [10]. The resultant current vector associated with phase windings in Eq(7) is of constant magnitudeI_m and rotates at a constant angular velocity of rad/s around the stator.

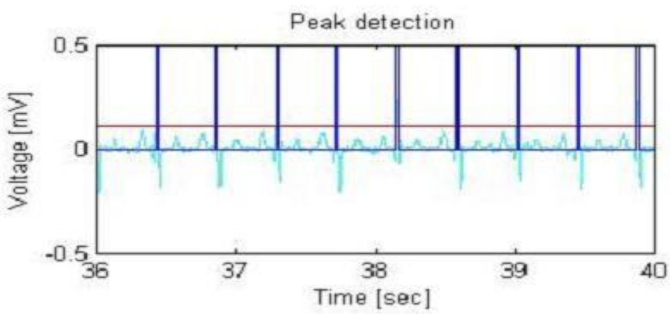


Figure 5. Peak detection

V. RESULTANT MAGNETIC AND ELECTRICAL VECTORS OF A THREE-PHASE STATOR

The application of the equivalent circuit of Fig. 3(c) to each phase winding of the three-phase, two-pole stator shown in Fig. 1, whose phase windings are displaced from each other by 120^0, and energized by three-phase voltages, produces the magnetic and electrical quantities of each phase winding along the phase magnetic axis as shown in Fig. 6.

Each magnetic or electrical phase variable can now be summed vectorially to produce the resultant of that variable [10]. Hence, the resultant magnetic field intensity H_{res}, flux densityB_{res}, flux ϕ_{res}, flux linkage λ_{res}, current vector i_{res}, and supply voltage $V_{res}$are given by the vector addition of their phase variables shown on the magnetic axes of Fig. 6. Applying the method utilized earlier to determine the resultant current vector associated with a phase winding to the above mentioned magnetic and electrical resultant vectors, the resultant magnetic and electrical vectors associated with a phase winding are given by:

The error between the actual running speed of the motor and the reference value is calculated and the control mechanism is executed by using a PI controller in this case.

The control signal is then given to a PWM generator which then produces the required gating signals that are to be given the 6 IGBT switches. The switches act according to the gate pulses given to them and the speed of the motor is controlled to the required value. The function of the proportional term of the PI controller is to consider the current size of the error value only at the time of controller calculation, and the integral term of the PI controller eliminates offset and sums up the complete controller error history up to the present time, starting from when the controller was first switched to automatic.

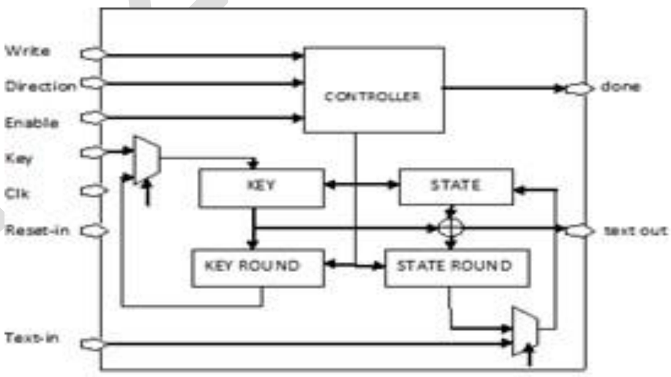
Sinusoidal pulse width modulation as shown in Fig 6.is employed in the circuit to turn on the switches. The extent, to which the dc voltage is boosted via the Z source network i.e. the boost factor, is decided by the modulation index of the pulse width modulation used.In an outer loop controlled induction motor drive, the actual rotor speed is compared with its commanded value, and the error is processed through a controller usually a PI controller and a limiter are used to obtain the slip-speed command. The limiter ensures that the slip-speed command is within the maximum allowable slip-speed of the induction motor. The slip-speed command is added to electrical rotor speed to obtain the stator frequency command. Thereafter the stator frequency command is processed as in an open loop drive. In the closed loop induction motor drive the limits on the slip speed, boost voltage and reference speed are externally adjustable variables. The external adjustment allows the tuning and matching of the induction motor to the converter and inverter and the tailoring of its characteristics to match the load requirements.

When only phase winding *aa′* of the three-phase stator is energized, the self inductance$L_a$of that winding is given by:

$$L_a=L_l+L_m \quad (8)$$

where $L_1$and $L_m$are the leakage and magnetizing inductances respectively of phase winding *aa′*. However, when the three-phase stator is energized with three-phase voltages, the mutual inductance between stator phase windings is $-L_m 2$ and both self and mutual inductances are included in the flux linkage of the phase winding resulting in:

Three phase induction motors are the most widely used in various industrial applications because of the following properties - self starting property; elimination of a starting device; robust construction; higher power factor and good speed regulation. But the induction motor is a constant speed machine which makes its applications pretty much limited. To increase the areas of application of the induction motor, its speed has to be controlled by varying the supply frequency. The advantage of speed control of the induction machine is that it can save the energy spent by the machine. For example, a speed reduction of about 20% can improve the energy savings upto 50% in a centrifugal pump. This means that an energy inefficient motor can be replaced by a variable speed machine given an efficient control system. The base speed of an induction motor is directly proportional to the supply frequency and the number of poles. Now since the number of poles is fixed in the motor design, the best way to control the speed of the motor is to vary the supply frequency. The torque developed by the motor is directly proportional to the ratio of the applied voltage and the supply frequency. The torque is kept constant by varying the applied voltage and the supply frequency and by keeping their ratio to a constant value.



.Figure6. Architecture of AES core

The torque speed characteristics also denote that:

1.The starting current requirement is lower.

2. The stable operating point of the motor is increased. The motor can be run at 5% of the synchronous speed upto base speed instead of running the motor from the base speed itself.

3. The acceleration and deceleration of the motor can be controlled by controlling the change of the supplyfrequency of the motor with respect to time.

The open loop Volts/Hz control of an induction motor is far the most popular method of speed control because of its simplicity and these types of motors are widely used in industry. Traditionally, induction motors have been used with open loop 60Hz power supplies for constant speed applications. For adjustable speed applications, frequency control is natural. However, voltage is required to be proportional to frequency so that the stator flux remains constant if the stator resistance is neglected.

VI. CONCLUSIONS

Vector analysis is widely used for the analysis, modeling and control of electrical machines. The methodmakes use of vector currents, voltages and magnetic variables but does not represent them in an equivalent circuit of the machine. This paper presents the development of an equivalent circuit for an electromagnetic system consisting of scalar electrical, vector electrical and vector magnetic sections and shows the production of a vector current from its scalar counterpart that leads to the production of vector voltages on the magnetic axis of the system. Resultant current, voltage and magnetic variable vectors associated with a phase winding of a three-phase stator are also developed together with a single vector voltage equation of the system.

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