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STEADY STATE ANALYSIS OF SELF-EXCITED INDUCTION GENERATOR

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ABSTRACT

Induction generators are increasingly used in non-conventional energy systems such as wind, mini/micro hydro etc. In isolated systems, squirrel cage induction generators with capacitor excitation, known as self-excited induction generators (SEIG), are very popular. Steady state analysis for such machines is essential to estimate the behavoir under actual operating conditions. A 5.5KW induction machine excited with symmetrical capacitor bank and loaded with resistive or resistive-inductive load was the subject of investigation. A simple mathematical model is proposed to compute the steady-state performance of self-excited induction generator by nodal admittance model. MATLAB programming is used to solve the proposed model. The results confirms the validity and accuracy of the MATLAB based modeling of self-excited induction generator.

KEYWORDS: Admittance Model, Magnetizing Reactance, MATLAB, Steady State Analysis, Self-Excited Induction Generator

INTRODUCTION

Due to industrial, agricultural and economic developments across the world, electrical power demand is increasing day by day. Such fast growing power demand and continuous depletion of fossil fuels have resulted the movement of scientists towards non-conventional resources such as wind, solar, biogas, tidal and geothermal. The wind energy is emerging as potential source among various non conventional energy sources. Almost every country across the world are promoting wind energy generation units [1]. Harnessing wind energy for electric power generation is an area of research interest and at present the emphasis is being given to the cost-effective utilization of these energy resources for quality and reliable power supply [2]. With their limitations, a renewable energy power plant is installed locally and equipped with a small-size generator, up to only a few MW rating [3]. Traditionally, synchronous generators have been used for power generation but induction generators are increasingly being used these days because of their relative advantageous feature over conventional synchronous generators [4].

The induction machine can be operated in grid connected or self-excited mode. Induction generator in self-excited mode is capable to generate the power even in the absence of power grid. This makes it to be most useful generator for remote windy locations [5]. The self-excited induction generators (SEIG) have been found suitable for energy conversion for remote locations. Self-excited induction generators are frequently considered as the most economical solution for powering costumers isolated from the utility grid. SEIG has many advantages such as simple construction, absence of DC power supply for excitation, reduced maintenance cost, good over speed capability, and self short-circuit protection capability [6].

A proper circuit representation and accurate mathematical modeling is essential to evaluate the steady-state performance of a SEIG for different operating conditions. Some researchers have used the impedance model [7]-[9] and a few used the admittance model [10]-[11] for steady state analysis of SEIG. Joshi *et al.*[12] presented a technique for steady state analysis of three phase SEIG feeding balanced unity power factor load using artificial neural network. Jordan *et al.* [13] proposed a multi-objective genetic algorithm based approach for determining the steady state performance characteristics of three-phase self-excited inductions generators operating in parallel and supplying an unbalanced load. Shakuntla Boora [14] presented mathematical models for various generator-load configurations that accurately determine the conditions for self-excitation and performance characteristics of an isolated, three-phase self-excited induction generator operating under balanced or unbalanced conditions. Chandan Chakraborty *et al.*[15] presented a new algorithmic method to study the steady-state performance of N number of induction generators connected in parallel. The method uses the inverse π circuit model to derive a closed form expression for frequency from the power balance equation. Ahmed E. Kalas *et al.*[16] used particle swarm optimization algorithm based technique to estimate and analyze the steady state performance of self-excited induction generator. In this paper we have proposed MATLAB language for the simulating the steady state analysis of self-excited induction generator. The performance characteristics with resistive and resistive inductive load are obtained.

SELF –EXCITED INDUCTION GENERATOR

The self excited induction generator takes the power for excitation process from a capacitor bank, connected across the stator terminals of the induction generator. This capacitor bank also supplies the reactive power to the load. Figure 1 shows a self-excited induction generator.

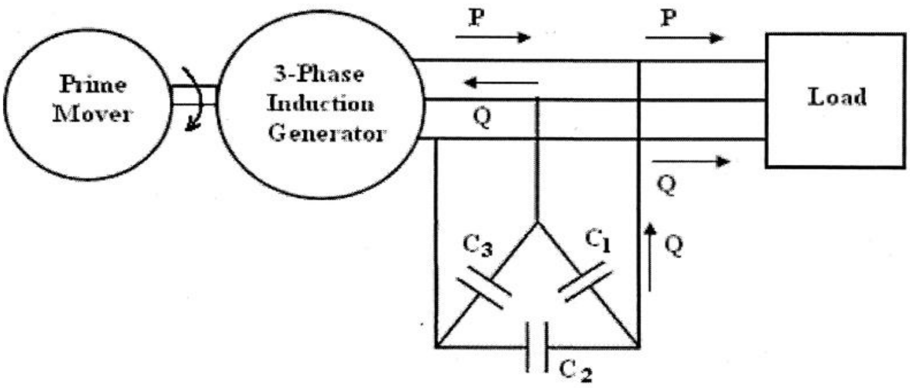

Figure 1: Self-Excited Induction Generator

The excitation capacitance serves a dual purpose for standalone induction generator: first ringing with the machine inductance in a negatively damped, resonant circuit to build up the terminal voltage from zero using only the permanent magnetism of the machine, and then correcting the power factor of the machine by supplying the generator reactive power [17]-[18]. It has its inherent advantages such as brushless construction with squirrel-cage rotor, reduced size, absence of DC power supply for excitation, reduced maintenance cost, and better transient performances. Major drawbacks of SEIG are reactive power consumption, its relatively poor voltage and frequency regulation under varying prime mover speed, excitation capacitor and load characteristics [19]. On the basis of the prime movers used and their locations, generating schemes can be broadly classified in to three types [20]: (i) the constant-speed constant-frequency, (ii) the variable-speed constant-frequency, and (iii) the variable-speed variable-frequency.

STEADY STATE MODEL OF THREE PHASE SELF-EXCITED INDUCTION GENERATOR

For the modeling of the self excited induction generator the main flux path saturation is accounted for while the saturation in the leakage flux path of magnetic core of the machine, the iron and rotational losses are neglected [21]. Most of the steady state models of SEIG developed by different researchers are based on per phase equivalent circuit. These models use the following two basic methods: (i) Loop impedance method and (ii) Nodal admittance method. The steady state model based on nodal admittance method and used in [22] is presented here in Figure 2. This model makes assumptions that the load is RL, machine core loss component is neglected and the machine parameters (except for magnetizing reactance) remain constant.

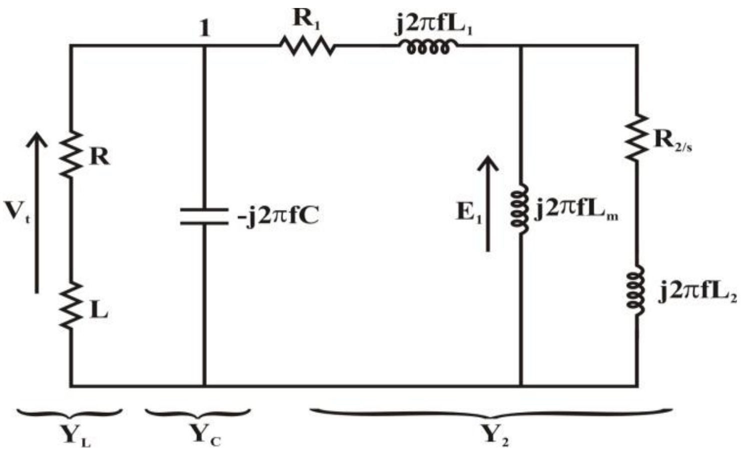

Figure 2: Equivalent Circuit of Self-Excited Induction Generator

For the machine to self-excite on load, the impedance line corresponding to the parallel combination of the load impedance and excitation capacitance should intersect the magnetization characteristic well in to the saturation region. For the self-excitation of the machine on no load, the excitation capacitance must be larger than some minimum value, this minimum value decreases with decreasing speed [23]. For the circuit shown in Figure 2, by using Kirchhoff's current law, the sum of currents at node (1) should be equal to zero, therefore

$$\mathbf{VY} = \mathbf{0} \tag{1}$$

Where **Y** is the net admittance given by

$$\mathbf{Y} = \mathbf{Y_L} + \mathbf{Y_c} + \mathbf{Y_2} \tag{2}$$

The terminal voltage cannot be equal to zero, therefore

$$\mathbf{Y} = \mathbf{0} \tag{3}$$

By equating the real and imaginary terms in equation (3) respectively to zero, we have

$$\mathrm{Real}(\mathbf{Y_L} + \mathbf{Y_c} + \mathbf{Y_2}) = \mathbf{0}$$

$$\mathrm{Imag}(\mathbf{Y_L} + \mathbf{Y_c} + \mathbf{Y_2}) = \mathbf{0}$$

PROBLEM FORMULATION AND PROPOSED ALGORITHM

Self excitation in an induction machine occurs when the rotor is driven by a prime mover and a suitable capacitance is connected across the stator terminals. Both the frequency and the magnetizing reactance (which depends upon magnetic saturation) of the SEIG vary with load even when the rotor speed is maintained constant [24]. Therefore, a crucial step in the steady-state analysis of the SEIG is, given the machine parameters, speed, excitation capacitance and load impedance, to determine the value of the per-unit frequency and the magnetizing reactance X_m which result in exact balance of active and reactive power across the air gap.

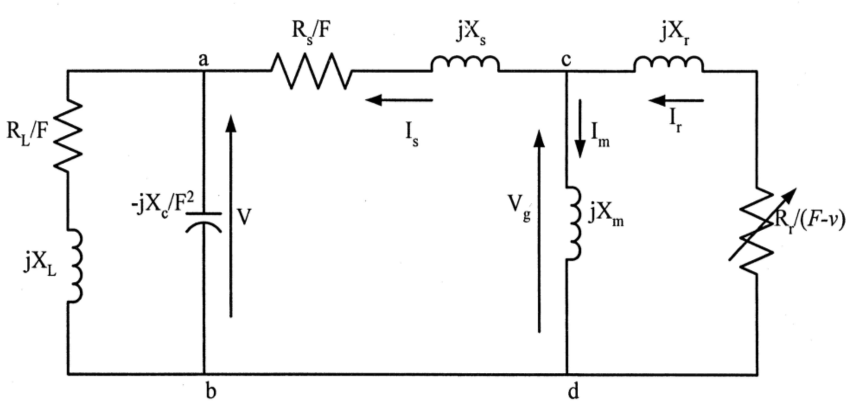

Figure 3: Per-Phase Equivalent Circuit of SEIG

Where:

R_s	:	p.u. resistance of stator per phase
R_r	:	p.u. resistance of rotor per phase
X_s	:	p.u. reactance of stator per phase (at nominal frequency)
X_r	:	p.u. reactance of rotor per phase (at nominal frequency)
X_m	:	p.u. magnetizing reactance per phase (at nominal frequency)
F	:	p.u. frequency
v	:	p.u. speed
X_c	:	p.u. reactance of shunt capacitor (at nominal frequency)
R_L	:	p.u. resistance of the load per phase
X_L	:	p.u. reactance of the load per phase (at nominal frequency)

The nodal admittance model is used for steady state analysis of SEIG [25].The per phase equivalent circuit of SEIG shown in Figure3 is used for problem formulation. The formulation of conservation of real and reactive power in terms of network quantities is equivalent to writing that the sum of the admittances of the branches in the circuit must be zero, as it is seen that this circuit does not contain any e.m.f. source or current source

$$V_g(Y_{bc} + Y_m + Y_r) = 0 \qquad (4)$$

Where,

$$Y_{bc} = \frac{1}{R_t - jX_t} = G_t + jB_t \qquad (5)$$

$$G_t = \frac{R_t}{R_t^2 + X_t^2} \qquad \& \qquad B_t = \frac{X_t}{R_t^2 + X_t^2} \qquad (6)$$

$$R_t = \left(R_{ab} + \frac{R_s}{f}\right) \quad \& \quad X_t = (X_{ab} - X_s) \qquad (7)$$

$$R_{ab} = \frac{R_L X_c^2}{f[f^2 R_L^2 + (X_L f^2 - X_c^2)^2]} \qquad (8)$$

$$X_{ab} = \frac{(X_L X_c^2 - f^2 X_L^2 X_c - R_L X_c^2)}{[f^2 R_L^2 + (X_L f^2 - X_c^2)^2]} \qquad (9)$$

$$Y_m = \frac{1}{jX_m} = -j\frac{1}{X_m} \qquad (10)$$

$$Y_r = \frac{1}{\frac{R_r}{(f-v)} + jX_r} = \frac{\frac{R_r}{(f-v)} - jX_r}{\left(\frac{R_r}{(f-v)}\right)^2 + X_r^2} \qquad (11)$$

For voltage build-up, $V_g \neq 0$, hence equation (4) becomes

$$(Y_{bc} + Y_m + Y_r) = 0 \qquad (12)$$

Equating the real and imaginary parts in equation (12) to zero, we have

$$G_t + \frac{\frac{R_r}{(f-v)}}{\left(\frac{R_r}{(f-v)}\right)^2 + X_r^2} = 0 \qquad (13)$$

& $$B_t - \frac{1}{X_m} - \frac{X_r}{\left(\frac{R_r}{(f-v)}\right)^2 + X_r^2} = 0 \qquad (14)$$

Let $\gamma = f - v$ (15)

Equation (13) can be rewritten as a quadratic equation in γ as:

$$G_t X_r^2 \gamma^2 + R_r \gamma + G_t R_r^2 = 0 \qquad (16)$$

Solving equation (16), we get

$$\gamma = -\frac{R_r}{2G_t X_r^2}\left\{1 \mp \sqrt{(1 - 4G_t^2 X_r^2)}\right\} \qquad (17)$$

In practice, γ □ is a small negative number for generator operation; hence the negative sign in the brackets of equation (17) should be taken.

$$\gamma = -\frac{R_r}{2G_t X_r^2}\left\{1 - \sqrt{(1 - 4G_t^2 X_r^2)}\right\} \qquad (18)$$

For a given rotor speed, load impedance and excitation capacitance, equation (13) may be used to determine 'f'. By using equation (14), we calculate the value of X_m as by given equation (19).

$$X_m = \frac{\left(R_L + \frac{R_s}{f}\right)\left[\left(\frac{R_r}{(f-v)}\right)^2 + X_r^2\right]}{\left[\left(\frac{R_r}{(f-v)}\right)(X_s - X_L) - X_r\left(R_L + \frac{R_s}{f}\right)\right]} \qquad (19)$$

After getting the value of X_m and f, find the air-gap voltage (V_g) by using the magnetization curve (plot of V_g v/s X_m), and solve the equivalent circuit for the performance parameters such as V_s, I_s, I_L, output power.

$$I_s = \frac{V_g}{f} Y_{bc} \tag{20}$$

$$V_s = \frac{V_g}{f} = I_s Z_{ac} \tag{21}$$

$$I_c = \frac{V_{ab}}{\left(-j\frac{X_c}{f^2}\right)} \tag{22}$$

$$I_L = I_s - I_c \tag{23}$$

$$P_{out} = V_{ab} I_L \tag{24}$$

The computational procedure of iterative method for solution of X_m and f and subsequent performance of SEIG using MATLAB are as follows:

Step 1: Read the machine data (R_s, X_s, R_r, X_r), prime mover speed, p.f. of load, synchronous speed test data etc.

Step 2: Assume an initial value of per-unit frequency 'f' and take the value of 'f' is equal to 'v' (f = v).

Step 3: Evaluate G_t using equations (6) - (9).

Step 4: Determine γ by using equation (18); hence obtain the updated value of 'f' using equation (15).

Step 5: Repeat steps (2) and (3), each time using the updated value of 'f' for evaluating G_t until the values of 'f' in successive iterations differ by a sufficiently small number ϵ.

Step 6: By getting the value of 'f', calculate the value of X_m by using equation (19).

Step 7: By using the magnetizations curve (V_g v/s X_m), determine V_g and correspondingly find the value of voltage and current across the load branch by using eq. (20) to eq. (24).

Step 8: Store the relevant data in data file.

Step 9: By using the values of the above calculated parameters, various characteristics that yield to the machine performance are obtained.

Step 10: Stop.

SIMULATIONS RESULTS AND DISCUSSIONS

The performance characteristics of 3-phase, 4-pole, and 50Hz, 415V, 5.83A, 5.5KW, delta-connected squirrel cage induction generator has been obtained using MATLAB. The per-phase equivalent circuit constants in per unit are as follows:

$R_s = 0.0633$; $R_r = 0.0247$; X_s=0.0633; X_r=X_s; pf = 0.8; v = 1 p.u.

The following three types of characteristics are obtained with resistive load and resistive-inductive load for load power factor 0.8pf lagging and excitation capacitance 20μf.

Variation of Magnetizing Reactance with Output Power

The variation of magnetizing reactance with output power for resistive and resistive-inductive load is shown in Figure 4. For resistive load, the loading is more than resistive-inductive load. The variation of magnetizing reactance is nearly constant for resistive load and increases sharply for resistive-inductive load. These characteristics are calculated for excitation capacitance of 20μf and load power factor 0.8 lagging.

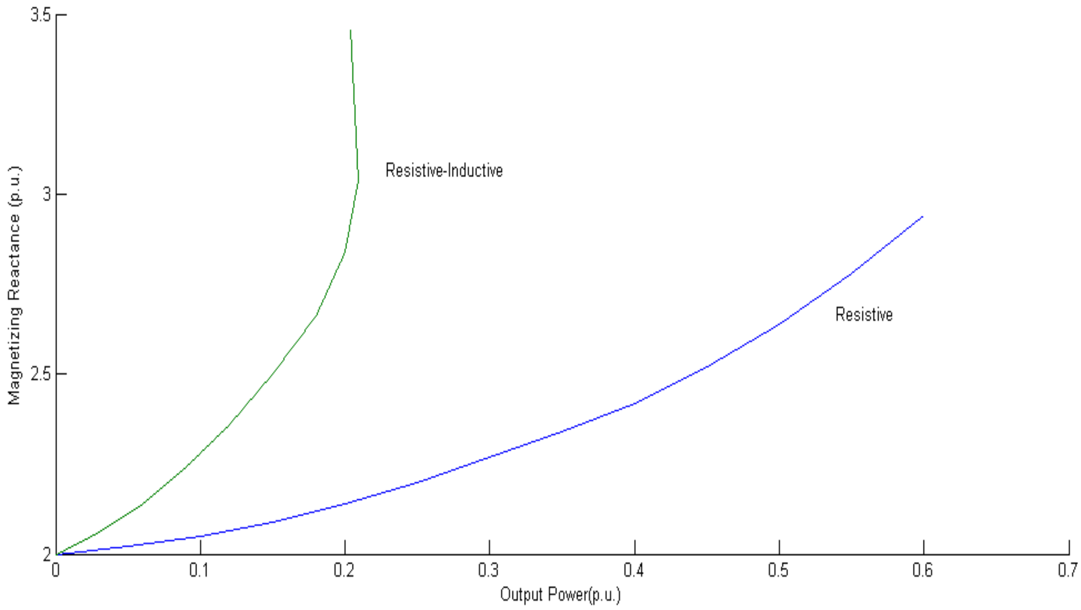

Figure 4: Variation of Magnetizing Reactance with Output Power

Variation of Terminal Voltage with Output Power

The variation of terminal voltage with output power for resistive and resistive-inductive load is shown in Figure 5. For resistive load, the terminal voltage decreases gradually while for resistive-inductive load the terminal voltage decreases rapidly. These characteristics are calculated for excitation capacitance of 20μf and load power factor 0.8 lagging.

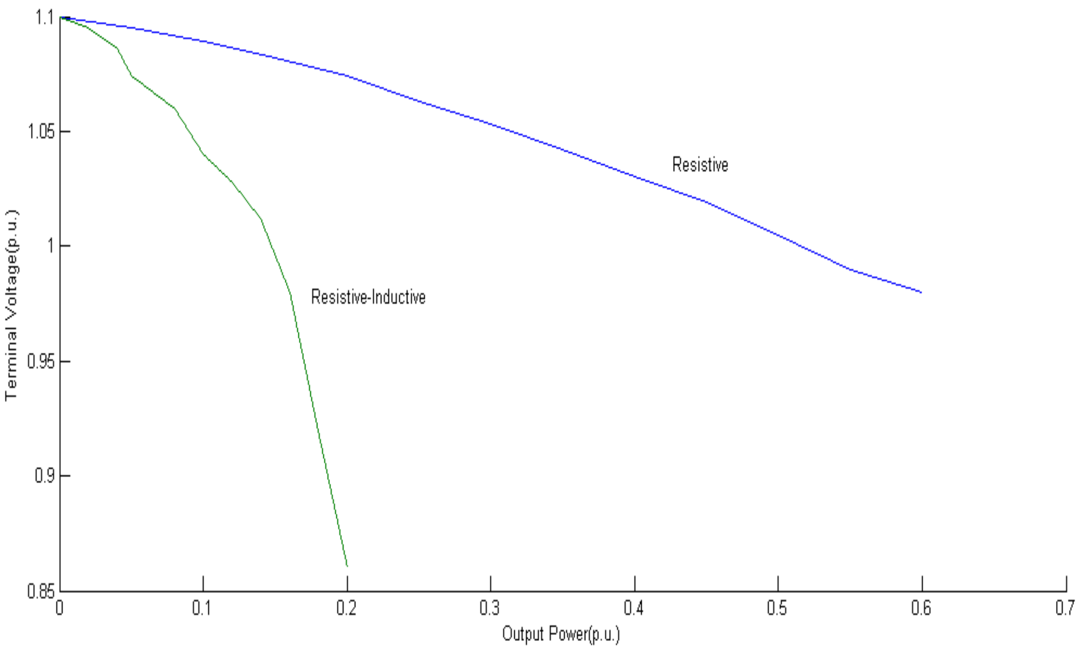

Figure 5 Variation of Terminal Voltage with Output Power

Variation of Load Current with Output Power

The variation of load current with output power for resistive and resistive-inductive load is shown in Figure 6. For resistive load, the self-excited induction generator draws more current and the output loading is also more as compared to resistive-inductive loading. These characteristics show that loading capacity is more for resistive load as compared to inductive loading. These characteristics are calculated for excitation capacitance of 20µf and load power factor 0.8 lagging.

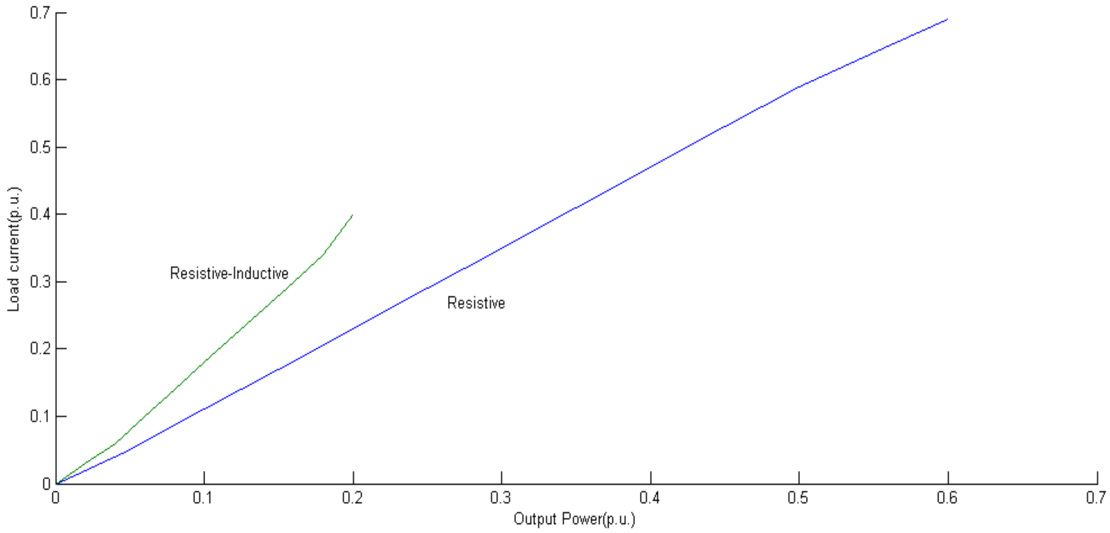

Figure 6: Variation of Load with Output Power

CONCLUSIONS

An efficient but simple technique has been developed for steady-state analysis of self-excited induction generator. The proposed steady state analysis might be helpful to wind generation, can be utilized by the interested users or the normal utility to feed loads where frequency and voltage need not be regulated. The steady-state characteristics show that loading capacity of SEIG is more for resistive load as compared to inductive loading. The proposed method for steady-state analysis of SEIG involves only simple numeric calculations, in contrast to existing methods which require tedious and complicated algebraic derivations, but accuracy is extremely good and convergence is fast.

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