Evaluating the Value of the Excitation Capacitance of a Wind Turbine/Induction Generator System Using Genetic Algorithms

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Evaluating the Value of the Excitation Capacitance of a Wind Turbine/Induction Generator System Using Genetic Algorithms

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***Abstract*—Due to their robustness, low cost, and low maintenance, induction generators are good candidates for wind energy systems. In addition, when the wind turbine is isolated from the grid, the induction generator can operate within a wide speed range which utilize maximum power extraction. To ensure that voltage buildup will take place between the machine terminals, the reactive power required by the machine must be supplied. To achieve that, a three phase capacitor bank is connected to the generator terminals. Evaluating the adequate value of the capacitance is very crucial since it affects the value of the generated voltage. In this paper, the desired operating voltage and the corresponding value of the magnetizing inductance are defined from the magnetizing curve. By using genetic algorithms (GAs), the corresponding values of the excitation capacitance and the rotor slip are evaluated. Matlab/Simulink model is then used for validation. It is noticed that there is a good agreement between the values predicted by the GAs and the ones obtained from the simulation.**

Keywords—Capacitive excitation; genetic algorithms; self-excited induction generator; stand alone wind energy system; Wind turbine.

I. INTRODUCTION

Recently, there has been growing interest in relying on sustainable and clean sources of energy due to environmental and economic reasons. One of the most promising sources of renewable energy is wind energy [1]-[11]. Some studies predicted that by the next decade, the wind energy could possibly supply 10% of the energy required by the globe [6].

Wind energy may be harvested using wind turbines. The wind turbine is composed of a turbine which convert wind energy into rotational mechanical energy and a generator which convert the mechanical energy into electrical energy. The generator may be a DC machine [1], [2], a synchronous machine [3]-[5], or an induction machine [6]-[11]. Due to the presence of brushes and commutator segments, DC generators have low reliability and require very frequent maintenance.

Synchronous generators may seem as a good choice due to their high efficiency. However, a DC supply is required for the field winding which add to their cost. Permanent magnets can replace the DC supply but magnets are subject to partially or fully losing their magnetism which reduce the reliability and the robustness of the synchronous generator. Another drawback of the synchronous generators is that they operate at a fixed speed (synchronous speed) which preclude the maximum power tracking.

Induction generators on the other hand are relatively cheap, easy to construct, robust, and almost maintenance free. In addition, they can operate at variable speed and thus they can be utilized for maximum power tracking. Since induction machines are inductive, the reactive power required by the machine must be supplied before voltage build-up can occur. When the wind energy system is grid connected, the reactive power required by the induction generator is supplied by the grid. When the wind energy system is isolated from the grid, a three phase capacitor bank is connected between the machine terminals to supply the required reactive power [6]-[10].

Another requirement for successful voltage build-up is the existence of residual magnetism in the rotor. Similar to DC shunt generators, residual magnetism will produce small voltage between the stator terminals which in turn increase the rotor magnetism due to the flow of the capacitive current which again increase the voltage. The build-up process will continue until saturation takes place which limit the value of the generated voltage.

For a given rotor speed, the value of the capacitance will decide the value of the generated voltage. To calculate the required capacitance, two non-linear equations need to be solved [9], [10]. The first equation relate the rotor slip to the machine parameters and the excitation capacitance. The second equation relate the magnetizing reactance to the machine parameters, the excitation capacitance, and the rotor slip. Given that the desired operating point is defined from the magnetizing curve, it is very difficult to solve the two equations analytically. Also for accurate prediction of the generated voltage and the rotor slip, the machine parameters and the magnetizing curve should be evaluated.

In [9] and [10], it was assumed that the value of the excitation reactance was specified. Then for a given rotor speed, the value of the magnetizing reactance was evaluated using the two equations. From the magnetizing curve, the corresponding value of the no-load voltage was obtained. However, it is typically

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desired to specify the voltage and then evaluate the corresponding value of the excitation reactance.

In this paper, the machine parameters and the magnetizing curve are obtained experimentally in the lab. After defining the value of the desired generated voltage, the corresponding value of the magnetizing reactance is obtained from the magnetizing curve. Then genetic algorithms (GAs), [12], is used to evaluate the value of the excitation capacitance and the rotor slip. Matlab/Simulink model is then used to validate the values predicted by GAs.

The organization of this paper will be as follows: In Section II, the equivalent circuit of the induction machine is defined. Setting up the equations which are used to evaluate the excitation capacitance is considered in Section III. Section IV discusses the using of GAs for solving equations. Case study is presented in Section V. Finally, the work of this paper is concluded in Section VI.

II. Equivalent Circuit of an Induction Machine

The equivalent circuit of a three phase induction machine is introduced in this section. The equivalent circuit model shown in Fig.1 is a very common model which has been proven to predict the performance of the machine within a reasonable accuracy [13]. The parameters R_1 and X_{l1} are the stator resistance and leakage reactance respectively, R_2' and X_{l2}' are the referred rotor resistance and leakage reactance respectively, and X_m and R_c are the magnetizing reactance and core resistance respectively. Since the value of X_m is a function of the magnetizing current I_m and the value of R_2'/s is a function of the machine slip S, arrows are used to indicate that as depicted in Fig.1.

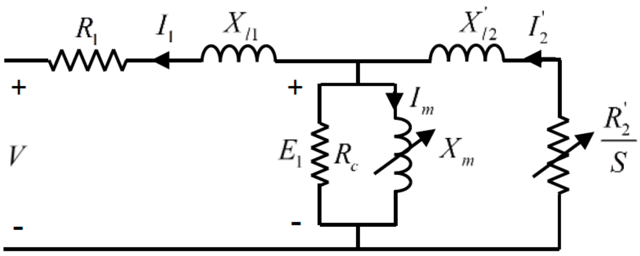

Fig. 1. Equivelant circuit of an Induction generator

In this paper, it assumed that the core loss is negligible and therefore, R_c may be eliminated from the equivalent circuit. The rest of the parameters will be evaluated experimentally in the laboratory.

III. Excitation Capacitance Evaluation

Predicting the value of the excitation capacitance and the operating frequency of the induction generator at a given shaft speed and when the load and the peak value of the phase-to-neutral voltage are specified is considered herein as the fundamental problem. While the machine reactances are functions of frequency which depend on the rotor speed and the slip, the slip is also a function of the output power. In addition, the output power depends on the terminal voltage which depends on the value of the excitation capacitance and the frequency. Furthermore, the value of the magnetizing reactance is operating-point-dependent.

This coupling between the machine parameters and performance equations lead to a very complicated problem. The first step to resolve this problem is to consider the Steinmetz circuit model shown in Fig.2 with the core loss being neglected. As shown, the load resistance and the excitation reactance are dedicated by R and X_c.

The equivalent circuit resistances and leakage reactances may be derived from the no-load test and the locked rotor test. To evaluate the magnetizing reactance, it is required to construct the no-load curve as a relationship between the no-load current and the no-load voltage.

The no load curve may be obtained by applying a variable, three-phase, ac voltage at rated frequency to the machine terminals while it is being driven at synchronous speed corresponding to rated frequency. Under these conditions, the input phase current I_1 equals the magnetizing current I_m, and thus E_1 is given by [10]:

$$E_1 = X_m I_1 \tag{1}$$

where

$$X_m = \left(\sqrt{\left(\frac{V_1}{I_1} \right)^2 - R_1^2} - X_1 \right) \tag{2}$$

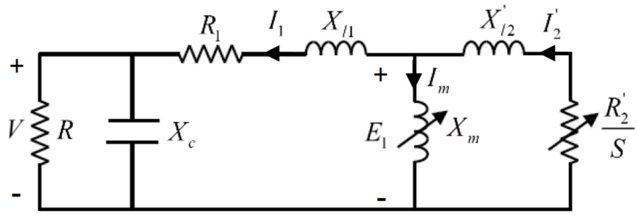

Fig. 2. Equivelant Circuit with Ressitive Load and Excitation Reactance

The load in the circuit depicted in Fig.2 is represented by a resistance R and a shunt excitation reactance X_c. To simplify analysis the load is replaced by an equivalent load resistance R_L in series with an equivalent load capacitive reactance X_L as illustrated in Fig.3

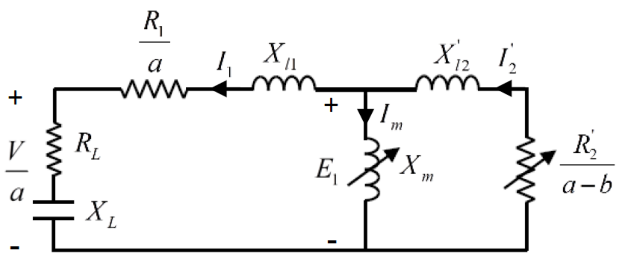

Fig. 3. Equivelant circuit with Series Equiavlent Load

Since the operating frequency of the induction generator is a function of the load resistance and excitation capacitance, it is more convenient to represent the equivalent circuit in terms of the reactances calculated at rated frequency. This can be achieved by defining the parameters a and b as [10].

$$a = \frac{actual\ frequency}{rated\ frequency} \quad (3)$$

$$b = \frac{actual\ speed}{synchronous\ speed\ at\ rated\ frequency} \quad (4)$$

If $\bar{Y}s$ represents the complex admittance of the stator circuit, $\bar{Y}_m = -j/X_m$, and $\bar{Y}r$ represents the complex admittance of the referred rotor circuit, then conservation of both active and reactive power may be defined as:

$$E_1^2\bar{Y}_s + E_1^2\bar{Y}_m + E_1^2\bar{Y}_r = 0 \quad (5)$$

and thus,

$$\bar{Y}_s + \bar{Y}_m + \bar{Y}_r = 0 \quad (6)$$

To satisfy the conservation of the real power, the sum of the real part of the admittances must be equal to zero as follows

$$\frac{(R_L + R_1/a)}{(X_1 - X_L)^2 + (R_L + R_1/a)^2} + \frac{R_2/(a-b)}{X_2^2 + (R_2/(a-b))^2} = 0 \quad (7)$$

The conservation of reactive power yields

$$X_m = \frac{(R_L + R_1/a)\left[X_2^2 + (R_2/(a-b))^2\right]}{(R_2/(a-b))(X_1 - X_L) - X_2(R_L + R_1/a)} \quad (8)$$

If the desired peak value of the phase-to-neutral voltage is specified then the value of X_m is evaluated using the no-load curve and equation (2). Given that the shaft speed is known, the value of *b* may be obtained. This yield two equations (7) and (8) with two unknowns *a* and X_c. One can notice that it is very difficult to solve these equations analytically and therefore, genetic algorithms, GAs, is used to solve these equations. This will be discussed in the next section.

IV. SOLVING EQUATIONS USING GAS

Genetic Algorithms (GAs) is a population-based optimization tool [12]. Unlike traditional methods which search for the optimum solution using a single value for each iteration, GAs search for the solution using large number of values per iteration called population. The number of iterations conducted to converge to the solution is called the number of generations. The use of a population of estimates enhances the chance of converging to a global optimum instead of a local one [12].

A. Design Parameters

The first step to solve an optimization problem using GAs is to define the range of the design parameters which represent the unknown parameters. These parameters should have a solution set which correspond to a global optimum. The goal of the genetic algorithms is to find this solution set.

To define the design parameters, the minimum value, the maximum value, the encoding type, and the chromosome number are specified. The two unknown variables in equations (7) and (8), are defined as the design parameters as depicted in Table I.

TABLE I. DESIGN PARAMETERS

Parameter	*a*	X_c (Ω)
Minimum Value	$1*10^{-2}$	1
Maximum Value	3	$1*10^{3}$
Encoding	Logarithmic	Logarithmic
Chromosome	1	1

To ensure a rapid search for the solution, the parameter range is defined as logarithmic. Both design parameters are assigned to the same chromosome.

B. Fitness Function

Genetic algorithms cannot be used to solve equations directly since this optimization tool is based on maximizing the fitness function. Therefore, it is required to define a fitness function which has a global maximum that coincide with the solution of equations (7) and (8). First, two objective functions are defined as follows

$$O_1(a, X_c) = \frac{(R_L + R_1/a)}{(X_1 - X_L)^2 + (R_L + R_1/a)^2} + \frac{R_2/(a-b)}{X_2^2 + (R_2/(a-b))^2} \quad (9)$$

$$O_2(a, X_c) = X_m - \frac{(R_L + R_1/a)\left[X_2^2 + (R_2/(a-b))^2\right]}{(R_2/(a-b))(X_1 - X_L) - X_2(R_L + R_1/a)} \quad (10)$$

The solution of equations (9) and (10) which yield the values of X_c and *a* is obtained when $O_1(a, X_c) = O_2(a, X_c) = 0$.

As mentioned earlier, GAs is used to obtain the maximum value of the fitness function. Therefore, the fitness function is defined as

$$f_1(a, X_c) = \frac{1}{|O_1(a, X_c)| + |O_2(a, X_c)| + \varepsilon} \quad (11)$$

where ε is a very small positive value to ensure that the denominator of (11) is never equal to zero. The maximum value of the fitness function in (11) is acquired when $O_1(a, X_c) = O_2(a, X_c) = 0$ which correspond to the desired solution.

V. CASE STUDY

A. Calculation of Machine Parameters and no-load Characteristic Experimentally

In this section the laboratory work is conducted on a 3-ϕ, two-pole, induction machine with a line voltage of 380 V, and a rated current of 1.2 A. The induction machine/dynamometer test setup depicted in Fig. 4 is used to evaluate the machine parameters and the no-load curve experimentally.

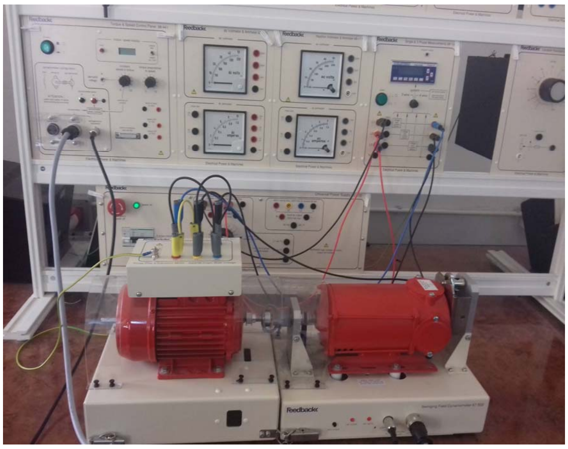

Fig. 4. Induction Machine/ Dynamometer Test Setup

The stator and the rotor resistances and leakage reactances are evaluated from the no-load test and the locked rotor test [13]. The values obtained from the tests are illustrated in Table II.

TABLE II. MACHINE PARAMETERS OBTAINED EXPERMINTALLY

Parameter	Symbol	Unit
R_1	33.5	Ω
X_{l1}	24.2	Ω
R_2'	31.94	Ω
X_{l2}'	24.21	Ω

To evaluate the no-load curve, three phase 50 Hz variable ac voltage source is applied to the stator winding while the machine is running at the synchronous speed (3000 rpm) [6], [7]. As a result, the machine is running at zero slip and thus the rotor branch is open due to infinite rotor impedance.

By changing the magnitude of the ac supply in steps and measuring the stator current at each step, the relationship between the no-load phase-to-neutral voltage and current is obtained as depicted in Fig. 5.

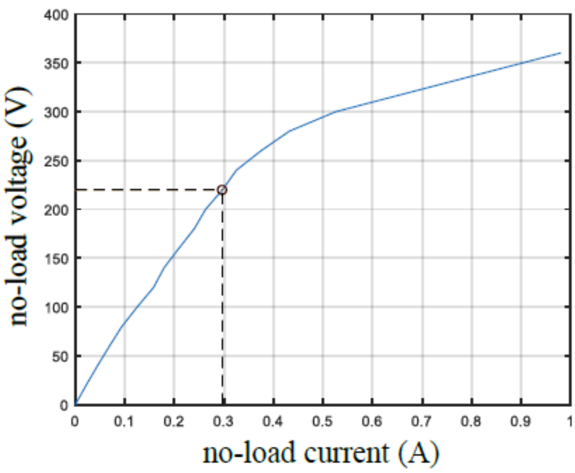

Fig. 5. No-Load Characteristic

Given that the stator resistance and leakage reactance are calculated from the no load and the blocked rotor tests, the magnetizing reactance may be obtained using equation (2) and the no-load curve depicted in Fig. 5.

B. GAs Results

In the previous section, the design parameters and the fitness function were defined. In this section the value of the excitation capacitance is evaluated. To set the stage, the desired no-load phase-to-neutral voltage is set to 220 V. The corresponding value of the no-load current is calculated from the no-load characteristic as denoted by the circle and the dotted lines in Fig. 5. Then the value of the magnetizing reactance may be obtained using equation (2). In the study herein, it is assumed that the rotor is running steady at 1600 rpm.

The genetic algorithms optimization is conducted with a population size of 1200 and for 1200 generations. As shown in Fig. 6, the optimization converges well to two values of a and X_c respectively. It should be noted that the range of each parameter is normalized such that the minimum and the maximum values defined in Table I correspond to zero and one respectively. However, the values of a and X_c are obtained directly and are not calculated using Fig.6.

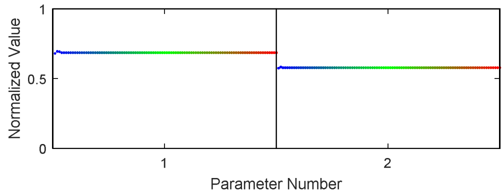

Fig. 6. GAs Result

The actual values obtained by the GAs for two values of R are shown in Table III

TABLE III. GAS RESULT

R (Ω)	X_c (Ω)	a
∞	205.7	0.53
366	135.3	0.486

C. Matlab/ Simulink Model of The Wind Turbine System

After obtaining the values of the resistances, leakage and magnetizing reactances and the value of the excitation capacitive reactance which obtained by the GAs, A Simulink model of the wind turbine system can by derived as shown in Fig.7.

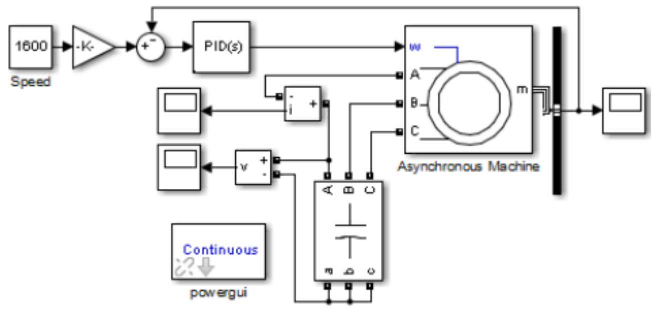

Fig.7. Simulink Model of the Wind Turbine System

The PI-controller shown in Fig.7 is used to ensure that the rotor speed will follow the commanded speed. The proportional gain is set to 10 and the integral gain is set to 30.

Using the no-load characteristic and equations (1) and (2), the magnetizing reactance is modeled as a relationship between

E_1 and I_m ($I_m = I_1$ at no-load). This relationship is obtained by giving the magnetizing current several values between zero and one and then calculating the corresponding air-gap voltage for each value. This model will automatically extrapolate any value outside this range.

To obtain the steady state values, the simulation is run for 10 seconds. From the simulation results, two cycles of the phase-to-neutral voltage wave-form for the no-load case is depicted in Fig. 8. One can notice that the maximum value of the phase-to-neutral voltage is about 220 V which is the same as the desired voltage.

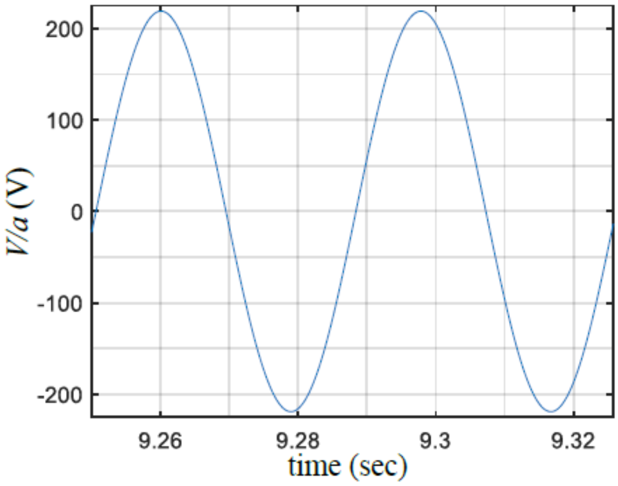

Fig.8. Phase-to-neutral voltage waveform

Fig.9 shows the magnetizing current waveform for the no-load case. It can be noticed that the maximum value of the magnetizing current waveform almost matches the value of the no-load current at the operating point depicted in Fig.5.

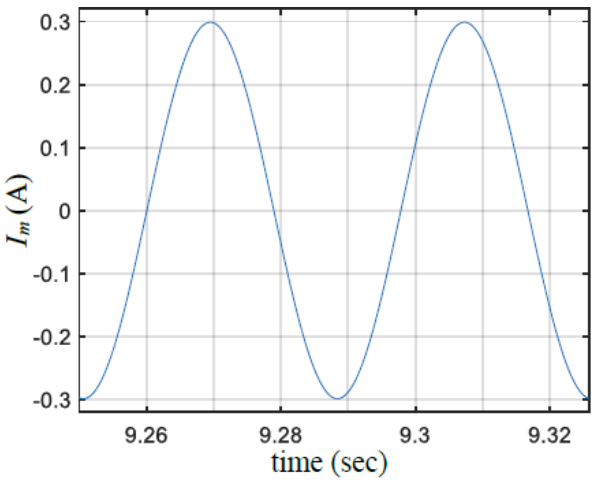

Fig.9. Magnetizing current waveform

D. *Comparison Between GAs and Simulation Results*

A comparison between the values of V/a, a, and the frequency f which are predicted by the GAs and the ones obtained by the Simulink model is presented in Table IV. The good agreement between the two results gives more confidence in the GAs method in evaluating the value of the excitation capacitance.

TABLE IV. COMPARISON BETWEEN FEAS AND SIMULINK MODEL

Parameter	*V/a* (V)	*a*	*f* (Hz)
GAs	220	0.53	26.5
Simulation	219	0.528	26.4

Fig. 10 shows the effect of the load on the phase-to-neutral terminal voltage. When a resistance of 366 Ω is connected between the generator terminals at $t = 4$ seconds, the value of the compensation reactance should be changed to the corresponding value shown in Table III. It should be noted that the value of the excitation capacitance is slightly increased to account for the voltage drop on the stator impedance.

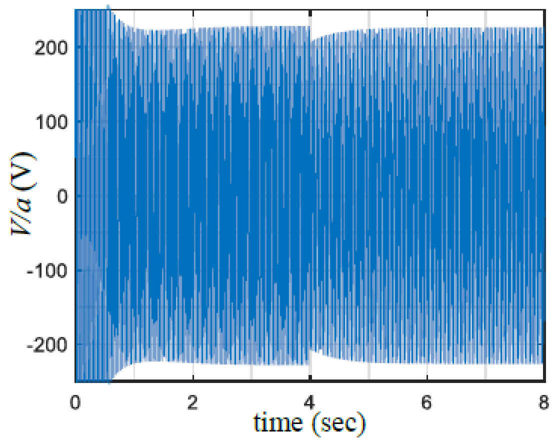

Fig.10. Effect of the load on phase-to-neutral voltage waveform

The effect of the load on the current wave-form is shown in Fig. 11

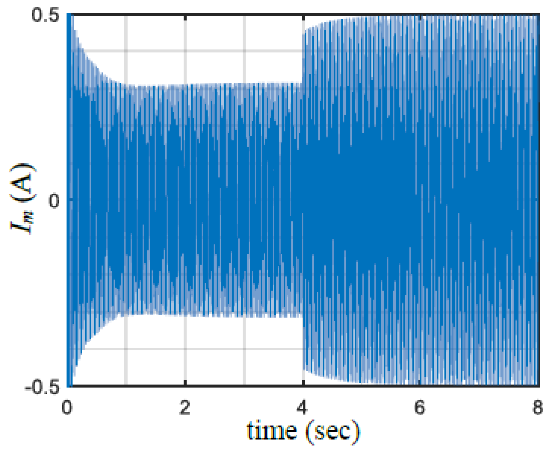

Fig.11. Effect of the load on current waveform

VI. CONCLUSION

In this paper, the excitation capacitance required for voltage build-up of a self-excited induction generator is evaluated using GAs. To set the stage, the machine parameters and the no-load characteristic are obtained experimentally. A Simulink model of the wind energy system is then derived using the value of these parameters and the value of the excitation capacitance predicted by the GAs. A good agreement between the GAs results and the results predicted from the simulation is achieved.

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