INVESTIGATION OF THE TRANSIENT BEHAVIOUR OF THREE PARALLEL CONNECTED SYNCHRONOUS GENERATORS WITH LARGE LOAD CHANGES AND CONTROL OF ACTIVE AND REACTIVE POWER USING EMTP

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Abstract To investigate the angular stability in a network of parallel connected synchronous machines, all system components that have influence on the transient behaviour of the total system must be taken into account. In this paper it is examined, wether a loaded asynchronous motor can be started up, when three parallel connected salient-pole machines feed the asynchronous motor. A detailed model for 30 MVA size synchronous machines, which includes electromechanical transient behaviour, is developed. Other models were also used in the simulation such as transient performance of non-rotating electrical components, the hydraulic systems of two different hydroelectric power plants (run-of-river power station and pumped-storage power station), and the influence of active and reactive power control where the network also contains four transformers and a 110 kV transmission line system of the whole length of 120 km. The calculated parameters are compared with measured quantities.

Key words: transient angular stability, hydraulic system, dynamic mechanical load

I. INTRODUCTION

Three parallel-connected operating salient-pole machines feed a loaded induction machine (squirrel cage rotor) on start up. Two synchronous machines are being propeled by Pelton turbines and the third synchronous machine is propeled by a Kaplan turbine. The induction machine (8.5 MVA) drives a cooling system. The electrical 110-kV transmission system consists of three generator transformers, one step-down transformer, and overhead power transmission lines (Figure 1). In this paper it is investigated wether the three in parallel working synchronous machines can start up the induction machine (loaded dynamically). During this electromechanically transient phase, the power frequency in the *separate network* is investigated. The power angles of the synchronous machines are investigated and resultant predictions about angular stability are derived. Detailed models of the electrical and mechanical components are derived and presented, with the emphasis on the modelling of the hydraulic system, the synchronous machines and the dynamic load.

II. NETWORK MODELLING

Starting point for the modelling of the *separate network* is the complete network structure (Figure 1).

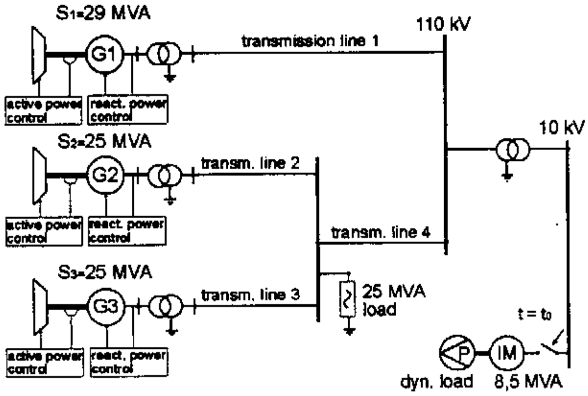

Fig. 1: Separate three-phase network containing all components used in the simulation

A. *Modelling of the synchronous machines*

Synchronous machines are often simply represented by a constant-voltage source with an impedance of constant value in series. This impedance has a constant value (the synchronous reactance X_d and the armature resistance R_a), and therefore the transient behaviour of different transient phases cannot be described with this model. Furthermore, the influence of the voltage-control system, the speed governing system and the magnetic saturation effects cannot be taken into account with this model. To describe the dynamic behaviour of a synchronous machine more precisely (including control systems), higher order models will be necessary. The mathematical network equations of such models contain time variant parameters. The inductive coupling of rotor fields on the stator is described by coupling impedances. To avoid time dependent coupling impedance values, the electrical network equations will be transformed with the *dq0-*

transformation. Armature quantities refer to the rotor. A so called *two-axis system* is obtained, where the electrical quantities of the stator (voltage, current and inductive fields) refer to the rotor. Hence, one obtains the following equivalent circuits for the *d-axis* (a) and the *q-axis* (b) circuits (Figure 2).

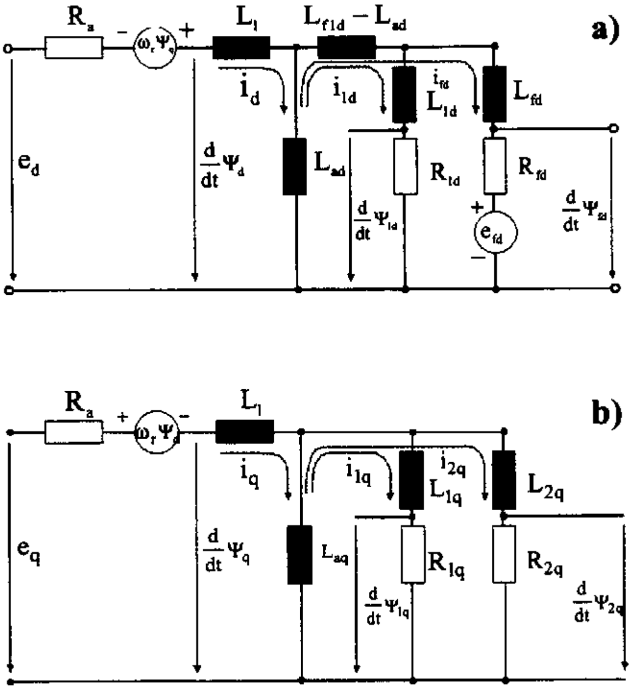

Fig. 2: Equivalent electrical circuit for a synchronous machine

Saturation effects occur when the excitation current reaches a much higher value than nominal value. The magnetization characteristic then becomes non-linear. The relation between no-load voltage of the stator and excitation current is non-linear. The voltage control system (reactive power control) can directly bias the excitation voltage and may cause high excitation currents. This is the reason why also these effects were considered in this simulation. Saturation effects were taken into account using a current-voltage characteristic for the unloaded synchronous machine. Saturation effects in the rotor and stator material caused by the voltage control system were considered. The mechanical properties of the synchronous machines (rotating masses) were also considered, because the power frequency depends mostly on the rotor speed of the synchronous machines. The moments of inertia of all three synchronous machines are relatively small, and therefore the influence of the active power control is of great importance for the power frequency in the *separate network.*

B. Modelling of the rotor, shaft system and turbine

For large shaft systems it is necessary to consider the torsion of the shaft, because one can obtain additional degrees of freedom for the dynamics of shaft oscillation. Generally, a common moment of inertia (D) for the rotor, shaft and turbine describes the basic mechanical behaviour of the shaft system. In this case the shaft is considered as a stiff connection between turbine and generator. In reality, such simplifications can be made only if the shaft is very short or the stiffness (K) of the shaft material is very high. Frequencies of 0.2 Hz up to 2 Hz can occur in common shaft systems. Those oscillations are subsynchronous oscillations that can interact with electrical resonant systems having similar eigen-frequencies. Figure 3 shows a shaft system for one synchronous machine is demonstrated.

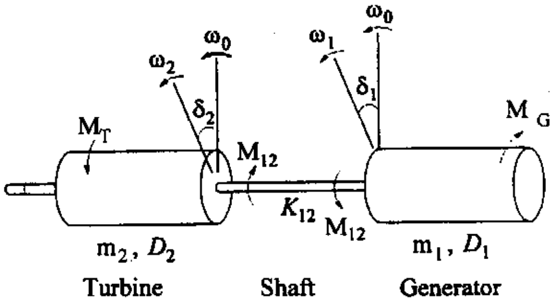

Fig. 3: Modelling of rotating masses

C. Modelling of the hydraulic system

An increase of the electrical active Power P_e at the synchronous machine terminals leads to a deceleration of the rotor speed. As soon as the rotor speed ω_r decreases, the mechanical power of the turbine system starts to increase due to actions of the active control system. Particulary for *pumped-storage power plants,* the rise-time of the mechnical power is in the range of some seconds. The reason for this is the acceleration time of the water mass in the *penstock.* Another reason is the finite velocity of the *actuators.* Non-linear output characteristic of *actuators* and *limiters* in the hydraulic system is considered in this model of the hydraulic system and the turbine (Figure 4). Modelling of a hydraulic system in EMTP can be done representing all components of the system with transfer functions. Each single transfer function has its own characteristic time constants, obtained from measurements in the real system or manufacturers' data (Figure 5). The dynamic of the active power control system and the hydraulic system determines the long-term stability behaviour of the complete *separate network.*

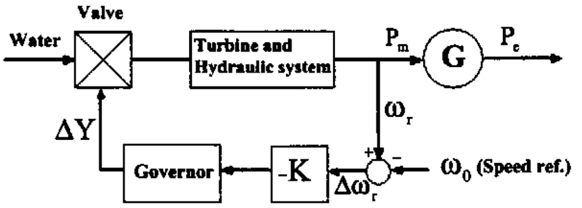

Fig. 4: Active power control and representation of the hydraulic system

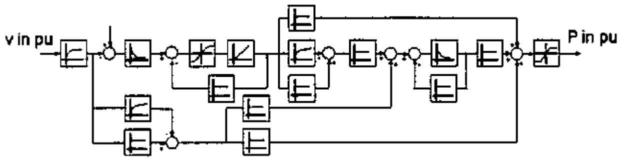

Fig. 5: Modelling of the turbine and hydraulic system

Therefore the behaviour of the dynamic of the active control system and the hydraulic system is investigated under large electrical load changes P_e. If electrical load changes exceed a certain level, the dynamic of the active control system and hydraulic system can be too slow to supply the turbine with mechanical power P_m. The synchronous generators would enter a domain of instability (angular instability). The unit-step response of the hydraulic system (inclusive turbine) is shown in figure 6 for the pumped-storage power plant and in figure 7 for the run-of-river power plant. One can see that the response of the *run-of-river system* is faster than the response of the *pumped-storage* system. The hydraulic system of the run-of-river power plant can supply mechanical power P_m faster than the hydraulic system of the *pumped-storage* power plant.

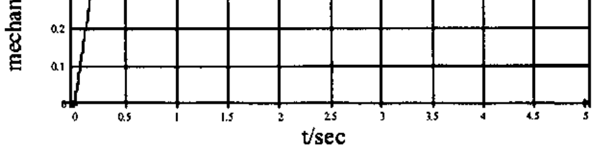

Fig. 6: Simulated response of the pumped-storage hydraulic system to a unit step

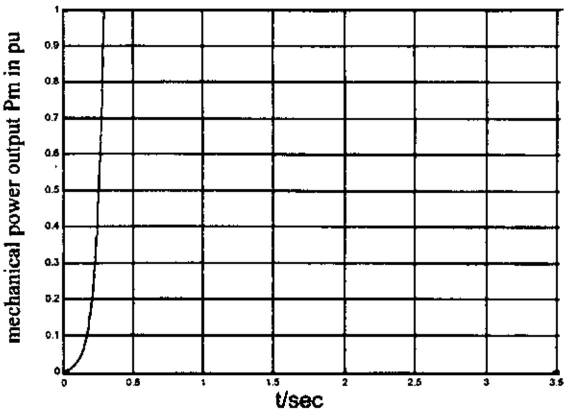

Fig. 7: Simulated response of the run-of-river hydraulic system to a unit step

D. Modelling of the reactive power control system

The terminal voltages of the synchronous generators are dependent on the electrical load P_e at the terminals of the synchronous generators. The reactive control systems directly influence the excitation voltages. This leads to a nearly constant voltage at the terminals of the synchronous generators, independently of the electrical load P_e. The parameters of the reactive control system were chosen in such a way that the dynamic properties of the control system coincide with measured properties over a frequency range of 0 Hz to 3 Hz. Over that frequency range, magnitude and phase of the model of the reactive control system are the same as in the measured case. The non-linear relation between magnetic flux in the iron and excitation current is also considered in this model of the reactive power control system.

E. Modelling of the dynamic mechanical load

The induction motor drives a pump in a coolant circuit. The induction motor starts up the pump at $t=t_0$. The speed-torque characteristic for the pump is illustrated in figure 8. During the start-up, the currents in the induction motor terminals reach a much higher value than the nominal value of the current. The torque at the pump shaft is a function of the rotational speed of the pump. The induction motor is a squirrel cage rotor with two pole pairs. The maximum rotational speed is therefore 157.08 radiant/s. In EMTP, a dynamic mechanical load can be represented by an electrical network. Mechanical units correspond to electrical units and therefore can be obtained easily by converting electrical quantities (in the electrical network representation) to mechanical equivalents.

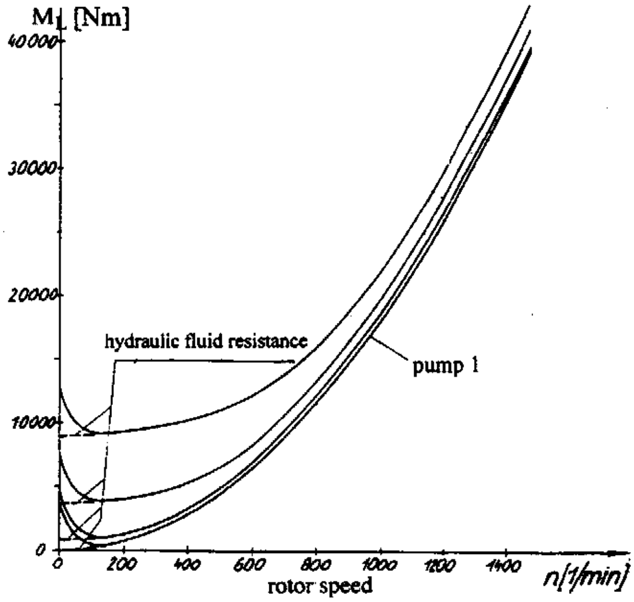

Fig. 8: Torque - Speed characteristic of the cooling pump (manufacturer data)

A mechanical load (mechanical torque) corresponds to an electrical current. Dynamic mechanical loads can be represented by controlled current sources. If the manufacturers data for a mechanical system is known, a detailed model of the mechanical system can be realized in EMTP with the help of TACS.

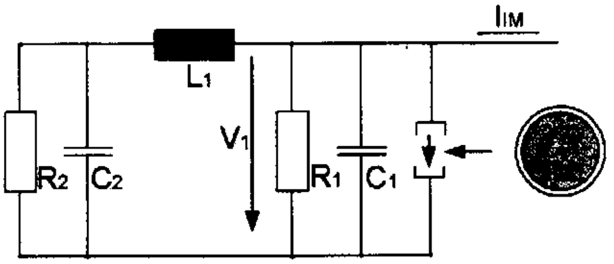

Fig. 9: Equivalent electrical circuit representing the dynamic mechanical load

In EMTP, an interface between mechanical and electrical quantities is implemented. The output values of the induction motor card are transformed into input values for the mechanical system and visa versa. For every time increment Δt of the simulation, the injected current I_{IM} leads to specific values in the mechanical network representation. Those values represent the rotational speed of the induction motor, the torque at the shaft, friction losses, etc.

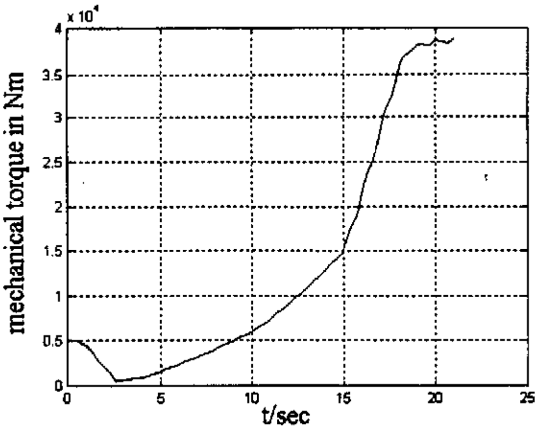

Fig. 10: Simulated Torque vs. time for the start-up of the induction motor

III. CALCULATED AND MEASURED RESULTS

In this chapter, the calculated results of the EMTP simulation will be compared with the measured results. This will be done for two cases:

1) Electrical power generating units are three synchronous machines (figure 1)
2) Electrical power supply unit is an infinite bus system

A. *Start-up time of the induction motor*

The start-up time of the induction motor for case 1 is longer compared to the start-up time in case 2. This results from the larger voltage-drop and frequency-drop for case 1 due to the lower short-circuit power of the three parallel-working synchronous machines. The frequency in case 1 drops from the rated frequency of 50 Hz to 48.2 Hz, which is also a reason for the slower start-up time of the loaded induction machine.

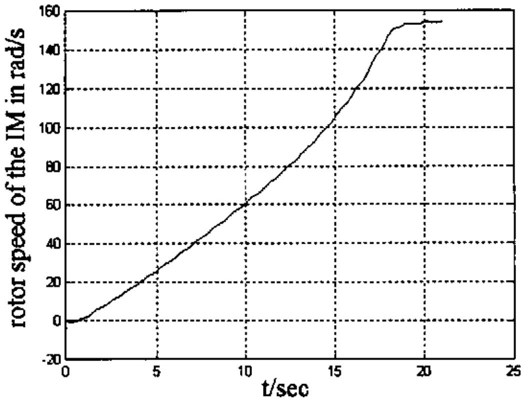

Fig. 11: Simulated rotor speed of the induction machine vs. time (case 1)

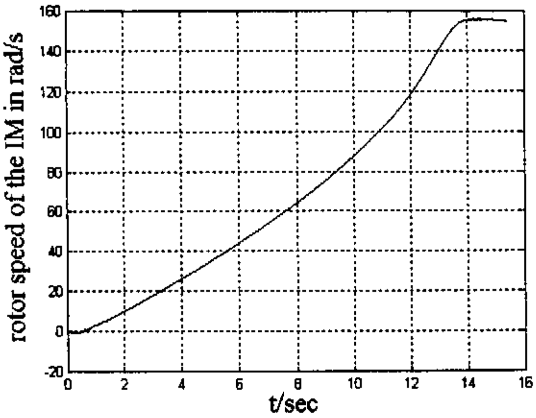

Fig. 12: Simulated rotor speed of the induction machine vs. time (case 2)

Table 1: Comparison of measured and calculated values of start-up times of the IM

	start-up time of the IM
case 2 (measured)	14.0 s
case 2 (simulation)	13.9 s
case 1 (measured)	22.0 s
case 1(simulation)	20.0 s

B. *Voltage and currents in the network*

During the first 8 seconds of the simulation (case 1), a voltage oscillation is superimposed to the terminal voltage of the step-down transformer of the induction motor (figure 13). This superimposed oscillation comes from the actions of the reactive power control systems and decays after 8 seconds. After 14 seconds, the voltage rises to a final steady state value. This is after the breakdown torque of the induction machine has been reached. A maximum value of the current in the terminals of the induction motor is reached at this time (2490 A) (figure 14).

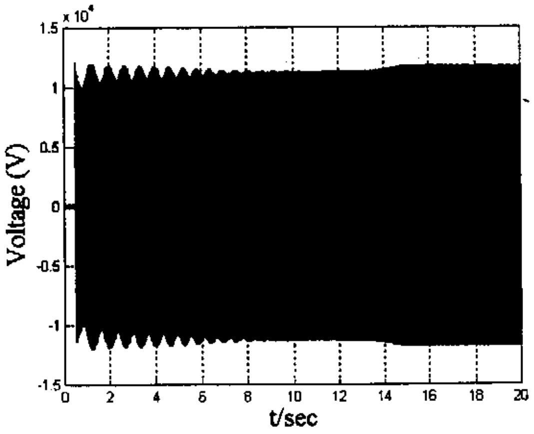

Fig. 13: Simulated voltage on the 110 kV-side (case 1)

After that time, the current in the terminals decreases and the voltage-drop in the electrical network elements decreases, too.

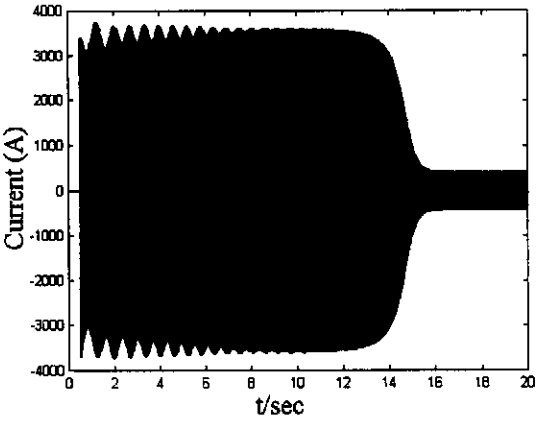

Fig. 14: Simulated current at the terminal of the induction machine (case 1)

Table 2: Comparison of measured and calculated values of the voltage

min. voltage at high voltage terminals of the transformer, feeding the induction motor	
case 1 (measured)	78.5 kV_{eff}
case 1 (simulation)	74.2 kV_{eff}

Table 3: Comparison of measured and calculated values of the current

max. Current in the terminals of the induction motor	
case 1 (measured)	2490 A_{eff}
case 1 (simulation)	2700 A_{eff}

C. *Power angles of the synchronous machines*

The *power angles* of all synchronous generators rise to a higher value after the induction motor is switched (t = 0.5 s). Generators G2 and G3 show the same electrical behaviour because both machines and control systems are the same. None of the *power angles* exceed a value of 90 degrees (1.57 radiant); therefore both synchronous generators remain in a stable operating condition. The slight rise in the *power angle* of synchronous generator G2/G3 (figure 16 a) is due to the active power control systems. After the simulation time length of 23 seconds the whole process of controlling the active power was not totally completed. Without active power control, the synchronous generators would not supply enough active power and the rotor speed would drop fast. This would lead to a large frequency drop in the electrical network and the induction motor could not start up.

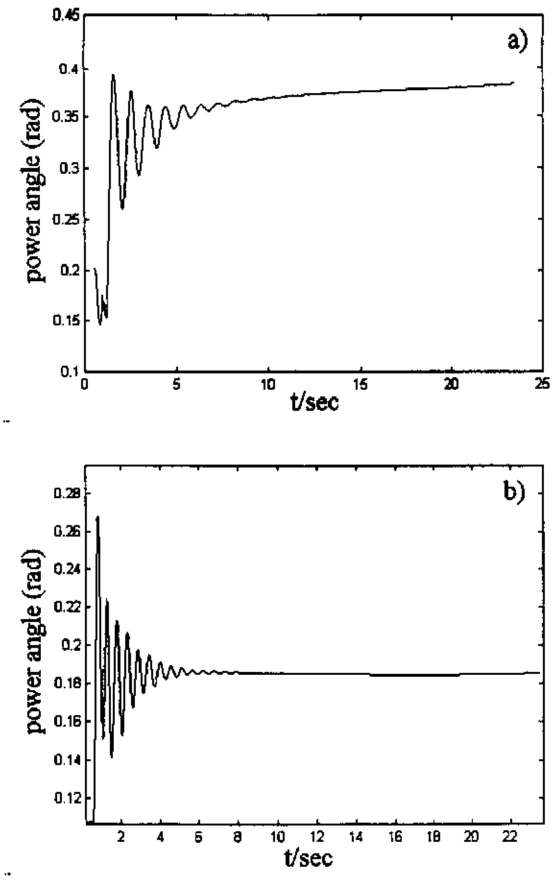

Fig. 16: Simulated power angles of synchronous machines G2/G3 (a) and G1 (b)

D. *Power frequency in the separate network*

A minimum value of the frequency (48.2 Hz) is reached shortly after switching the induction motor (figure 17). The active control systems and hydraulic systems follow this frequency drop after approximately one second and the synchronous generators supply additional active power. The steady state value of the frequency is 50.6 Hz due to the higher set-point value of the active power control (50.6 Hz). A set-point value of 50.6 Hz was chosen to get a faster compensation of the electrical active power lack. After 20 seconds, the frequency has reached its steady-state value (figure 17).

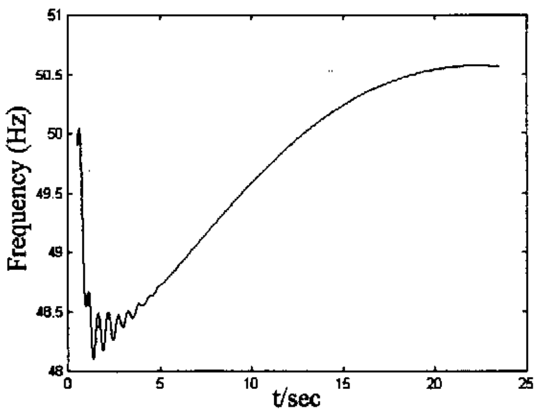

Fig. 17: Simulated power frequency (case 1)

Table 4: Power frequency

min. power frequency in the separate network	
case 1 (simulation)	48.2 Hz
case 2 (measured)	48.6 Hz

IX. CONCLUSION

This paper describes a detailed model of a *separate network* including control systems and representation of hydraulic systems. This model allows the investigation of transients in all network components as well as the dynamic behaviour of all system components during the start-up of a loaded induction motor. A time domain simulation with EMTP is performed. The analysis results are compared to measurement results. It was found that the loaded induction motor can start up and that the control systems and hydraulic system respond fast enough to provide the required active and reactive power.

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