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Evaluation of Dynamic Stability During a Symmetrical Three-Phase Short Circuit at Machine Terminals of Siah Bishe Pumped Storage Power Plant

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Abstract— This paper presents a survey on the research and applications of the pumped storage plants based on the published papers in trying to provide a suitable picture of the development of this electric load regulation approach. Moreover, the paper summaries two separate pumped storage power plants projects, one in America (Seneca) and another in Iran (Siah Bishe) from the following point of view:

- ***The operation of power plant generator/motor during day and night***
- ***Introduction of starting system in motors state***
- ***Technical, economic and environmental aspects of such power plant***
- ***Determination of system efficiency***

Since there are some experiences with Siah Bishe power plant project, the performances of the plant in dynamic stability improvement of the network following a symmetrical short circuit is analyzed. Based on the obtained results, it becomes clear that the plant can have great effect on the recovery of the network dynamic and transmitted energy between the synchronous machines installed in the plant and the network. High speed response is the most important factor which enhances the small signal stability of the system. This function of the plant can be critical in the fault events.

Index Terms— Pumped Storage, Dynamic Stability, load regulation, Siah Bishe power plant.

I. INTRODUCTION

One of the most suitable choices for electric load regulation in a power network is using Pumped Storage Power Plant, which plays an important role in optimum operation of network power. The system absorbs energy during off-peak and produces energy at peak load, which results in reduction of operation and production cost of energy at the base load power plant (Nuclear &Thermal) as well as need of peak power plant installation (Gas generator).

Pumped storage power plants employs synchronous machine for producing energy. Synchronous machine can deliver energy to the power network during peak load periods in the generator mode by flowing stored water from the upper reservoir to the lower reservoir and pump up water during off-peak hours in the motor mode. It leads to increase overall efficiency. In addition, with growing power networks and increasing stability problems, the storable energy systems with high speed response can be developing.

This paper consists of two main sections. In first section the pumped storage power plants is introduced and discussions about some relevant issues are presented. Then, the simulation results of dynamic behavior of synchronous generator in response to a three-phase fault at the machine terminals are obtained.

II. HISTORY OF PUMPED STORAGE POWER PLANTS IN THE WORLD

The use of water energy was discovered thousands of years ago. Thus, they applied water mills for producing energy. The first pumped storage power plant established in Zurich city of Switzerland in 1882. Another plant started up in Schaffhausen city of this country in 1909. Also, the first pumped storage power plant in England utilized in Walkerburn, in 1920.

After the world war two an economical explosion occurred in all over the world and demands for energy increased rapidly which result in transmission system development. These developed networks required power plants to meet the peak load hours.

Afterwards the pumped storage plants appeared for solving this problem. So these plants deployed in all over the world and more than 300 units started up at the end of year 1990. It indicates the effective role of pumped storage power plants in the world. In Asia, china has installed 11 pumped storage plants with a total capacity of 6.4 GW in 10 provinces. In addition, this county is starting up 10 pumped storage plants that are listed in Table I [1].

Table I. Major Pumped Storage Power Station Under Construction In China

No.	Project	Location province	Installed capacity (MW)	Average energy generation (TWh/year)

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1	**Tongguanshan**	**Jiangsu**	**1000**	**1.49**
2	**Tai'an**	**Shandong**	**1000**	**1.338**
3	**Xilongchi**	**Shanxi**	**1200**	**1.805**
4	**Baoquan**	**Henan**	**1200**	**2.01**
5	**Zhanghewan**	**Hebei**	**1000**	**1.675**
6	**Tongbai**	**Zhejiang**	**1200**	**2.118**
7	**Langyashan**	**Anhui**	**600**	**0.856**
8	**Bailianhe**	**Hubei**	**1200**	**0.967**
9	**Hemifeng**	**Hunan**	**1200**	**1.606**
10	**Huizhou**	**Guangdong**	**2400**	**4.563**

III. DESCRIPTION OF SENECA POWER PLANT PERFORMANCE AS A SAMPLE OF PUMPED STORAGE PLANT [2]

Seneca pumped storage plant has been installed in commercial service since January 14th, 1970. Synchronous starting of large reversible generator/motors by means of a small generator has proved to be highly reliable and the overall efficiency of the station ranges from 71 to 79 percent.

Seneca Plant is located on the Allegheny River near Warren, Pennsylvanua.

It was placed in commercial service January 14th, 1970. The plant contains two 220 MVA, 225 r/min generator/ motors and one 29 MVA, 514.3r/min generator, designated as Units 1, 2, and 3, respectively. The generator/motor units drive reversible pump/turbines which pump water during off-peak hours to a 6000 acre-foot upper reservoir from a pool formed by the Corps of Engineers' Kinzua Dam on the Allegheny River. Then, all three units use this stored water power to deliver energy to the power network during peak load periods. The plant was designed for a maximum output of 475 MW, with a daily capacity of 380 MW. It has since been rerated to a daily capacity of 455 MW.

Unit 1 is arranged to move water back and forth between the Allegheny Reservoir and the Seneca upper reservoir. The draft tube of the Unit 2 pump/turbine can be connected either to the Allegheny Reservoir or to the river downstream from the reservoir. Therefore, Unit 2 can operate between the Seneca upper reservoir and either the Allegheny Reservoir or the river. Unit 3, which is not reversible, generates power with stored water flowing from the Seneca upper reservoir to the river downstream from the Allegheny Reservoir.

Therefore, the energy which can be developed by the head created by the Allegheny Dam is partially recoverable. Unit 3 can take advantage of the head created by the dam on a year-round basis, while Unit 2 will have the use of the extra head approximately one-third of the year.

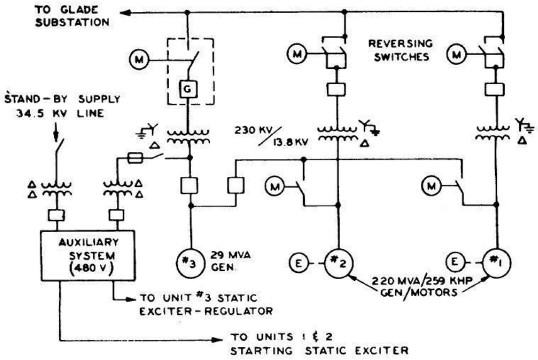

Fig.1. Single- line diagram of Seneca power plant

The single-line diagram of Figure 1 delineates the Main power and excitation connections. The generator/motors are started by the synchronous method with the Unit 3 generator when they are operated as motors. It is also possible to start either of the generator/ motors by the synchronous method by using the other as a generator.

They are equipped with both direct-connected rotating exciters and static rectifier exciters. The rectifiers, which are supplied with power from the station service system, are used to excite the machines when they are being started as motors. The direct-connected exciters are used for running excitation in both generating and motoring modes of operation. Unit 3 has only a solid-state rectifier excitation system.

Station service power is normally obtained from the Unit 3, step-up transformer, or Unit 3 if it is operated. Station power can also be taken from a Penelec 34.5 kV distribution line in case of trouble in the normal supply equipment, and a 500 kVA Diesel set will supply power to auxiliaries essential to the safety of the station if both main station service supply systems fail. The synchronous starting procedure is briefly as follows:

- Water in the draft tube of the pump/turbine is depressed with compressed air.
- Unit 3 and the generator/motor are connected together via the starting bus.
- The fields of Unit 3 and the generator/motor are excited.
- Unit 3 turbine wicket gates are opened.
- The two units accelerate in synchronism.
- At 90 percent speed the generator/motor field is switched from the rectifier to the rotating exciter.
- The generator/motor is synchronized to the system, with speed controlled by the Unit 3 governor and voltage controlled by the generator/ motor voltage regulator.
- The starting-bus circuit breaker is tripped and the 230 kV breaker associated with the generator/motor is closed.
- Compressed air is released from pump/turbine draft tube and pump is primed.
- Pump/turbine guard valve in penstock is opened.
- Pump/turbine wicket gates open and pumping begin.

A. Operating Experience

The present operating plan is to pump between 11:00 P.M. and 7:00 A.M. each day and to generate between 9:00 A.M. and 9:00 P.M. Monday through Friday. A typical weekday load profile is shown by Figure 2.

As the operation of Seneca pumped storage power plant has been shown that the synchronous method of starting a pump/turbine in the pumping mode can be made quite reliable, even with a generator less than 1/7 the size of the motor, that a pumped storage station has great operational flexibility, and that the overall efficiency can be in the order of 71 percent.

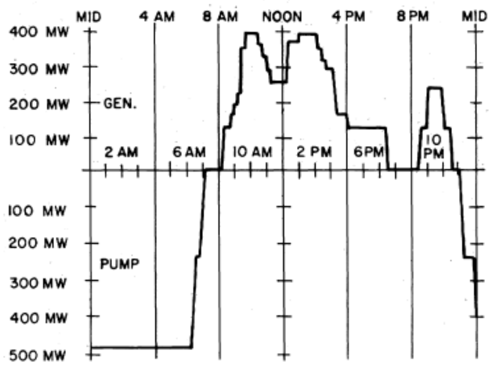

Fig.2. Daily loading profile of Seneca power plant

IV. HISTORY OF SIAH BISHE PUMPED STORAGE POWER PLANT IN IRAN [3]

Initial studies for the construction of pumped storage power plant in Iran started in 1970 when a Belgian consulting engineers company was requested to carry out such studies on Alborz mountains region within the frame work of an Iran-Belgian cooperation agreement. Initial report of the studies was prepared by the Belgian Tractionel Company and submitted to the ministry of energy.

Initial geological investigations began in early 1978. However, they were interrupted and came to a halt in the wake of the victory of the Islamic Revolution and departure of foreign consulting engineers from Iran. In 1983 phase II studies and preparation of tender documents began by Moshanir –Lahmeyer consulting Engineers joint venture and completed in 1985.

As from 1985 through 1992 supplementary studies and detail design works were completed by Moshanir- Lahmeyer Consulting Engineers joint venture. To accelerate construction works, certain parts of the project, including upper and lower dam diversion tunnels, part of access tunnel to the power house cavern, and part of power house drainage tunnel were completed until 1992 accompanied by the completion of blasting and field compaction tests.

All construction works that had come to a standstill during the period 1992- 2001, were resumed in 2002 by grouting works in diversion tunnels. Technical and economic review of the project, began by the French EDF and Moshanir Consulting Engineers in 1998, was completed in 2002.

V. TECHNICAL SPECIFICATION OF SIAH BISHE PROJECT

Siah Bishe pumped storage power plant is located in the vicinity of Siah Bishe village in Mazandaran Province 125 km to the north of Tehran and 10 km to the north of Kandovan Tunnel along Chalus River. The project takes its name from the nearly village of Siah Bishe.

A. Specification of Turbine Generator

Four vertical Francis turbine pumps will be installed in the power house cavern. Turbine maximum and minimum net heads will be 511.3 m and 460.6 m, respectively. With an average head, each turbines discharge and power output will be 62 m^3/s and 260 MW under generation mode, respectively, being reduced to 43 m^3/s and 220 MW for pumping mode. Main equipment for energy generation consists of four motor generators, one static frequency converter jointly used by each motor-generator, plus a high voltage substation.

Keeping balance in the national electricity network during peak hours and off-peak hours generation of hydro power energy during high-load consumption hours with a capacity of 1040 MW consumption of electric energy during low-load consumption hours with a capacity of 960 MW.

The specification of the turbine/generator and generation consumption capacity and its operation during day and night in motor/generator modes is demonstrated by Table II.

Table II. Specification Of Turbine/Generator

Turbine type	Francis pump turbine
Speed	500rpm
Turbine maximum net head	511.3m
Turbine minimum net head	460.6m
Downstream gates type	roller gate
Each turbines discharge	62m3/s
Each turbines discharge	during generation (62m^3/s)- during consumption(43m^3/s)
Each turbines power	during generation (260MW)- during consumption(220MW)

B. Technical Specification of Station and Its Connection to Network [4-5]

Siah Bishe station will be connected to the network by 400 kV (Ziran-Hasankeif) transmission line and 400 kV Vardavard line, which is under construction.

The station absorbs electrical energy from the network and offers the generated energy when it is needed. A switchyard with a type of (GIS) will be built at outdoor. The switchyard composes of three feeder line 400 kV and four transformer feeders. The relation between station and switchyard are transformer feeders. There are 13 single phase main transformer, that each of them has a capacity of 105 MVA with a ratio 18/400 kV. Moreover, there are two three phase auxiliary transformers with capacity of 5 MVA and ratio 18/20 kV is under installation.

C. SFC System and Its Startup in Turbine Generator/Motor Mode [6-7]

Static Frequency Converter (SFC) is used for electrical start of units in motor mode (water pumped) at Siah Bishe pumped storage power plant, while a generator (with a size of 1/7 of a motor) is used in Seneca pumped storage power plant. SFC is a static frequency inverter which supplies units in motor mode with variable frequency and voltage. It speeds up synchronization during pumping. The basic algorithm of SFC depends on rotor and speed as well as terminal voltage. Circuit model of the static frequency converter is shown in Figure 3.

SFC is composed of three phase power transformer with ratio 18/2 kV and the capacity of 18.6 MVA, which are fed by double cable that is connected to bays of 1 and 4.

This transformer has two output with the capacity of 9.3 MVA that send three-phase voltage 2 kV (AC) with current of 1792 A to rectifier bridge then voltage 2280 V and current 2194 A converts from AC to DC.

After that, inverter thyristor bridges converts DC to AC. The generated voltage and frequency can be changed to satisfying manner by thyristor bridge. In this system variable voltage from zero to 2 KV (AC) and variable frequency from zero to 50HZ creates from primary currents. The power output inverter can be more than power input however the efficiency can be high. The wave form is square, with using special filter and omitting surplus current harmonic as well as analyzing through Fourier, it can be possible to give satisfying sinus wave form to machine stator.

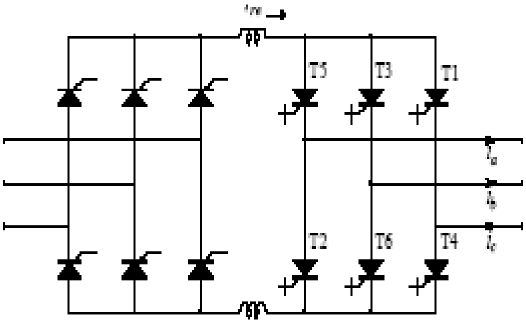

Fig.3. Circuit model of the Static Frequency Converter (SFC)

As mentioned the purpose of inverter is, feeding synchronous motor with variable voltage and frequency and its strategy divides into two stages:

- The first stage requires forced communication until 10% of the machine rated speed
- The second stage uses natural communication supported by voltage induced in the machine winding.

When thyristor is started, the speed of motor and I_{re} current of machine will be controlled and the current, based on fire angle of thyristor, injects while considering the real parameter. Figure 4 shows fire angle of thyristor stages.

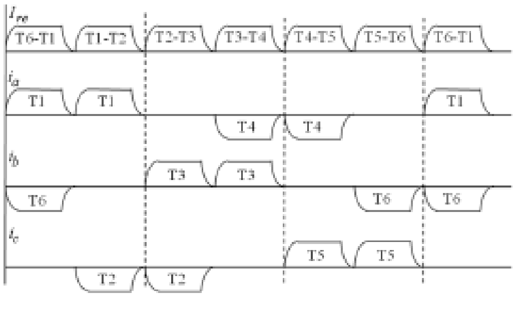

Fig.4. Phase current waveforms and forced commutation sequence in the inverter bridge (I_a, I_b and I_c are the machine line currents, I_{re} is the current at the DC interface of the SFC)

SFC operates at three stages:

- At the first stage inverter thyristor bridges convert variable voltage from zero to 2 KV (AC) and variable frequency from zero to 20 Hz in order to supply machine speed.
- Using transformer 18/2 kV for receiving synchronous speed (500 rpm) and frequency (50 Hz) is the second stage.
- Then, generator is synchronized with network by closing circuit breaker of unit, SFC outs from circuit and water is pumped by unit (motor mode).

VI. ECONOMICAL AND OPERATIONAL SPECIFICATION OF SIAH BISHE PROJECT [3-8-9-10].

Specifications of Siah Bishe pumped storage power plant from the economical and operational point of view are as follows:

- Using low price generated energy for pumping water is as the most economic factor to supply peak load. This kind of energy is useful, when consumption in the grid is low. Pumping of pumped storage power plant increases the load of thermal power plant so the efficiency becomes better and the operation becomes more economic.
- Fast starting at peak load of the power plant like gas plant is able to be started immediately. Changing from generator mode to motor mode or vise versa takes about two minutes. Therefore it prevents from sudden frequency caused by over loading or over generating [9].
- Economical construction of power plant in comparison with gas plant with the same capacity. According to studies, it is cleared that Siah Bishe pumped storage power plant with capacity of 1000 MW is more economical at peak load in comparison with 10 thermal plants with capacity of 100 MW. Studies show that 70 billion Rials were saved during 1984 to 2005.
- Voltage improvement and stability of 400 kV transmission network of Tehran Electric Company. As studies of Tehran Dispatching Center show [10] (2010) when the power plant and 400 kV connection line (Vardavard –Siah Bishe) start operating, the amount of 470 MW and 200 MVAR send to Tehran electric transmission network at peak load. It causes increasing voltage 400 kV at Vardavard and Kan station with amount of 9 kV.
- Siah Bishe pumped storage power plant is used for frequency control of Iran network. As loading determination shows: Generating 1040 MW of the power plant can be effect on increasing frequency about 0.309 Hz in 2011 and 0.289 Hz in 2012 in peak load of network [9].

VII. EVALUATION OF DYNAMIC STABILITY OF SYNCHRONOUS GENERATORS

In this section, the parameters of machine (reactances, resistances and time constants) are calculated by using nominal characteristics of the synchronous generators according to the datasheet of Siah Bishe pumped storage power plant. Then, equations of the machine are determined when these computed values are substituted. Finally, the performance of the machine is evaluated when it is subjected to a symmetrical three-phase fault at the machine terminal.

A. Machine Parameters [11]

Differential equations that describe the dynamic behavior of electrical machines are nonlinear. In the past, analyzing these equations was impossible but nowadays they can be solved by analogue or digital computers. There are two types of computer traces for simulating synchronous machines as follows:

1- Simulation by applying voltage equations in rotor reference-frame variables.

2- Simulation by applying stator and rotor flux linkage equations in arbitrary and rotor reference-frame variables, respectively.

In this paper, the first type has been used.

B. Machine Performance Evaluation

The purpose of this section is to study the dynamic behavior of the synchronous generator in response to a symmetrical three-phase fault at the machine terminals and sudden change in input torque [12].

The nominal characteristics of synchronous generator based on the datasheet of Siah Bishe pumped storage power plant are given in [11].

VIII. SIMULATION RESULTS [11-13]

The computer trace is delineated by Figures 5 to 9, illustrates the dynamic behavior of the machine in response to a symmetrical three-phase fault at the generator terminal. Assuming while generator speed equals synchronous speed, the input torque is changed from zero to nominal value ($0.9\times27.6\times10^6$ N.m). The machine is connected to an infinite bus when the voltage is equal to $1.6\times18000\times(2/3)^{1/2}$ at 50 Hz constant power frequency.

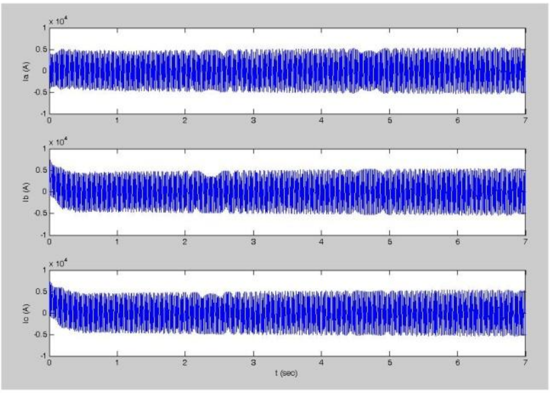

Fig.5. Behavior of currents I_a, I_b, I_c in response to a three-phase fault at the machine terminals.

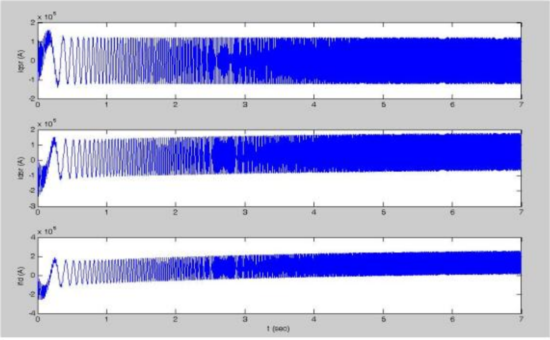

Fig.6. Behavior of currents I_{fd}, I_d, I_q in response to a three-phase fault at the machine terminals.

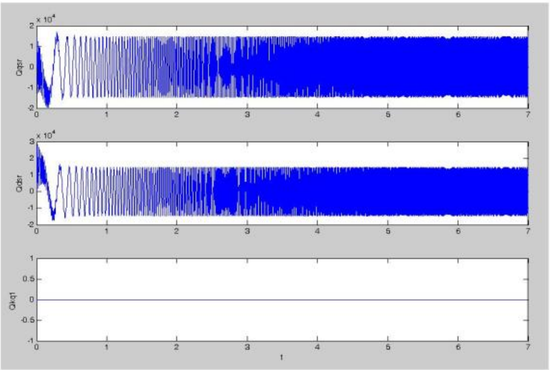

Fig.7. Behavior of fluxes Qkq1, Qd, Qq in response to a three-phase fault at the machine terminals.

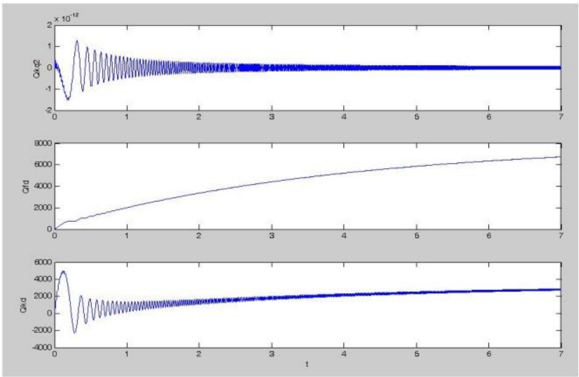

Fig.8. Behavior of fluxes Q_{kd}, Q_{fd}, Q_{kq2} in response to a three-phase fault at the machine terminals

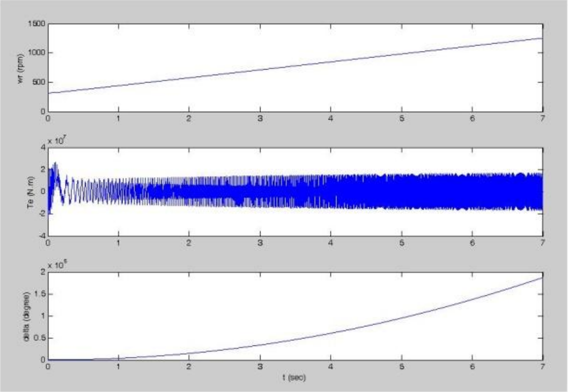

Fig.9. Behavior of δ, T_e, ω_r in response to a three-phase fault at the machine terminals.

IX. CONCLUSION

At first section of this paper two pumped storage power plants (Seneca in the U.S and Siah Bishe in Iran) introduced and the results have shown:

The overall efficiency of operating pumped storage power plant is better than thermal power plant from the economical point of view. For example,the efficiency of Siah Bishe plant and Seneca plant are about 77.9 and 71 percent, respectively [2-14].

The results which are obtained from the paper are as follows:

- Control simplicity can be provided which permits reliable remotely controlled automatic operation [15]. Siah Bishe pumped storage power plant can be controlled directly from Tehran Dispatching Center by energy management system (E.M.S.) [16].
- Useful time is effective on the efficiency of the thermal power plant connected to network for example (from generation and consumption point of view) this time is 66.5 hours and 116 hours for Siah Bishe plant and Seneca plant, respectively, during a week.
- As mentioned Static Frequency Converter (SFC) is used for electrical start of units in the motor mode (water pumped) at Siah Bishe pumped storage power plant, while a generator (with a size of 1/7 of a motor and the capacity of 29 MVA) is used in Seneca pumped storage power plant.

In the second stage of this paper, the dynamic behavior of synchronous generator was evaluated in response to a three-phase fault at the machine terminals and finally simulated by Matlab software. It was proved that the pumped storage power plants are useful to improve the network dynamic and transmit energy between machine and network. High speed response is the most important factor which makes system with damping in network transition state. This operation is important in network fault which results high load shedding.

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