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Optimal design of energy storage for load frequency control in micro hydro power plant using Bat Algorithm

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Abstract

The rotational speed of a generator affects the frequency and voltage produced, where this change will affect the load side. For that we need a control equipment that can optimize the performance of micro-hydro. Therefore, we need a technology to optimize the performance of micro hydro by applying Load Frequency Control (LFC). LFC designed by implementing Superconducting Magnetic Energy Storage (SMES) and Capacitive Energy Storage (CES), this application will provide power compensation to reduce or even eliminate frequency oscillations caused by changes in consumer electrical power loads. To get optimal microhydro performance, it is necessary to set the right parameters for SMES and CES. SMES and CES parameter tuning in this study is proposed using the Bat Algorithm. The objective function used by this algorithm is to optimize the Integral Time Absolute Error (ITAE). For performance analysis, the system is tested with load changes, then the governor, turbine, and system frequency responses are analyzed. To test the reliability of the system, this study used several scenarios of a combination of control, SMES, CES, with conventional control based on Proportional, Integral, Derivative (PID). The right control parameters will improve system performance more optimally. Optimal system performance can be seen from the response of the governor, turbine, and minimum overshoot of the frequency, as well as the fast settling time for the system to switch to steady state conditions.

Keywords:
Bat Algorithm;
Capacitive Energy Storage;
Micro hydro;
Overshoot;
Superconducting Magnetic Energy Storage;

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INTRODUCTION

The stability of the micro hydro power plant is a major concern in its operation because, at steady state operating conditions, the average speed for all generators must be the same or synchronous. The frequency and voltage of electricity generated by micro hydro are greatly influenced by the rotational speed of the generator, where changes greatly influence the rotational speed of this generator in load. At night, the electricity load supplied by micro hydropower will decrease, especially at 23.00 hours.

Because of this, the motion wheel rotates faster. As a result, the frequency of electricity increases and if it is too high, it endangers the consumer's electrical equipment. Therefore, to support the performance of micro hydro, frequency regulation is needed so that it is always in the work area between 49 Hz-51 Hz. The control mechanism is carried out automatically by adjusting the position of the gate opening so that the incoming water flow can be adjusted to the load. However, sudden changes in load cause the control mechanism to be not optimal. Therefore, a technology is needed to optimise the performance of the micro hydro unit, by applying Load Frequency Control.

The LFC mechanism is designed using Superconducting Magnetic Energy Storage (SMES) and Capacitive Energy Storage (CES), which can provide power compensation to reduce or even eliminate frequency oscillations caused by changes in the electrical power load of customers. It is necessary to tune the SMES and CES parameters optimally to be used properly to get good damping. The Bat Algorithm (BA) method is proposed in this study to optimise the SMES and CES parameters. The implementation of SMES and CES system frequency controllers produces optimal performance, such as [1, 2, 3, 4], which discusses the application of SMES in wind turbines and produces reliable wind turbines. Lastomo et al. discusses the application of SMES in multi-machine systems and produces an optimal system [5]. Djalal et al. discussed the application of CES to micro hydro to produce optimal micro hydro performance [6]. Finally, Djalal et al. discussed the application of SMES and CES to micro hydro based on Cuckoo Search to obtain optimal frequency settings for micro hydro [7]. In this study, the Cuckoo Search method’s optimisation results can still be improved with other algorithms.

Bat Algorithm (BA) is one of the algorithms introduced by Xin-She Yang in 2010 [8]. This algorithm is inspired by the behaviour of bats looking for food sources at night. The performance of the BA algorithm is very good in carrying out several optimisations, especially in the optimisation of the electric power system. The application of the BA method to the electric power system shows optimal results, such as [9] optimisation of the economical cost of generating, [10, 11, 12, 13], optimal optimisation of Power System Stabilizer parameters to improve power system stability, and [14] optimisation of optimal power flow to reduce losses in transmission. This research proposes an approach based on the Bat Algorithm as a more optimal SMES and CES optimisation method.

MATERIAL AND METHOD

Micro-Hydro Power Plant

Micro hydro is a small-scale power plant that uses hydropower as its driving force, such as irrigation canals, rivers or natural waterfalls by utilizing the height of the falls and the amount of water discharge. The mechanical energy generated from the turbine is then used to turn a generator to produce electrical energy. The mathematical representation of electric power generated from micro hydro can be described as given in (1) [15].

$$P_{th}[W] = Q[m^3/s].H[m].k[N/kg] \qquad (1)$$

P_{th} is the active power produced by the micro hydro and Q is the water flow to the turbine. k is the gravitational constant, and H is the water level. Active power relationship in addition, a complete representation of active power taking into account the efficiency of the turbine and generator is shown in (2) [15].

$$P_{real}[W] = Q[m^3/s].H[m].k[N/kg].\eta_{turbin}.\eta_{gen} \qquad (2)$$

For the analysis of the frequency stability of the micro-hydro system, it is modeled into a linear model consisting of a generator, turbine, governor, and servo motor, shown in Figure 1 [15].

Superconducting Magnetic Energy Storage

The working principle of SMES is to store energy in the form of a magnetic field generated from the superconductor coil. SMES consists of superconducting coil components, a cryogenic cooling system, and a Power Conditioning System (PCS). The function of the PCS is to transfer energy from the SMES coil to the system. PCS is also the power electronic interface between the SMES coil and the grid. Superconductors have small losses at cold temperatures. The SMES cryogenics consist of liquid helium, which can maintain a temperature at 4 K. A DC Link Capacitor is used to connect the source voltage from the SMES coil to the system.

The working principle of SMES consists of: charging, standby, and discharging [16]. To control the performance of SMES, it is done by adjusting the duty cycle (D) of the converter, using a thyristor Gate Turn Off (GTO). Figure 2 shows the SMES scheme depicted in (3)-(7).

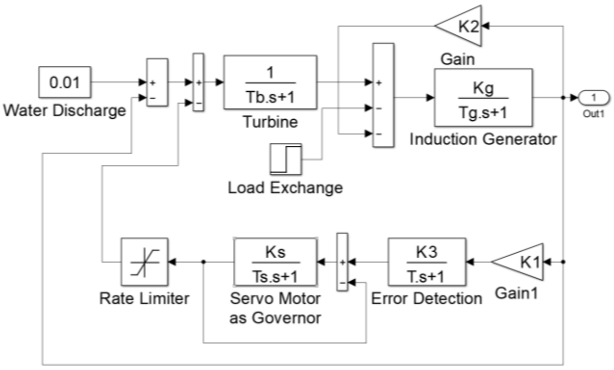

Figure 1. Micro hydro system

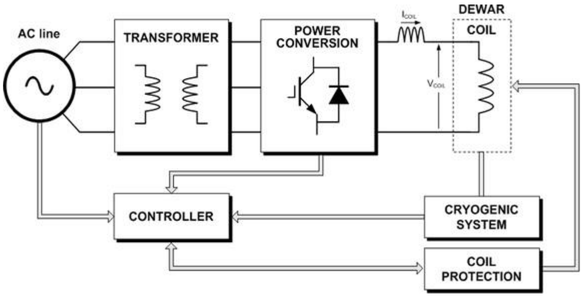

Figure 2. Schematic SMES

$$V_{SM} = D * V_{DC} \quad (1)$$

$$-V_{SM} = (1 - D) * V_{DC} \quad (2)$$

$$I_{SM} = \frac{1}{L_{SM}} \int_{t0}^{t} V_{DC} dt + I_{SM0} \quad (3)$$

$$P_{SM} = V_{SM} I_{SM} \quad (4)$$

$$W_{SM} = \frac{1}{2} L_{SM} I_{SM}^2 \quad (5)$$

Equation (3) is a description of the SMES mode in charging mode, where VDC is the Voltage in the DC Link Capacitor, D is the Duty Cycle, and VSM is the Voltage in the SMES Coil. Equation (4) is the mathematical model of SMES in discharge mode, and (5) is the SMES current. Equation (6) is the energy of the SMES, and (7) shows the energy of the SMES coil. Figure 3 shows the SMES configuration model.

Figure 4 shows the SMES modeling, where SMES starts from the input side in the form of $\Delta\omega$. Then the signal goes to the washout block with the washout time constant from SMES. Then the gain block is amplified with a constant SMES amplifier. Then Tdc is the Time Delay Constant of the SMES control component. The signal then goes to the rate limiter to limit the signal to the desired saturation condition. The next signal goes to the SMES inductance block with the Lsm parameter. From the ISM output, add Ido to the output. The output produced by Psm is used as input (compensation) on the generator while waiting for the governor to work.

SMES are placed at the generator terminals to control the power balance. The SMES-PID model is shown in Figure 4 [17][18].

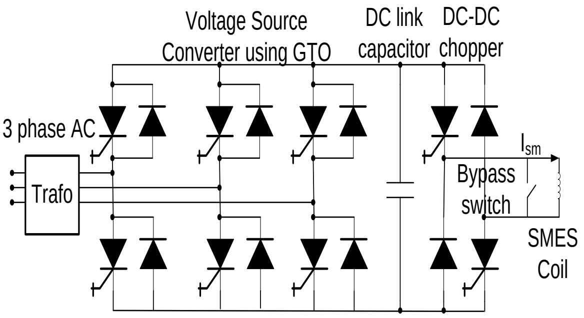

Figure 3. SMES configuration

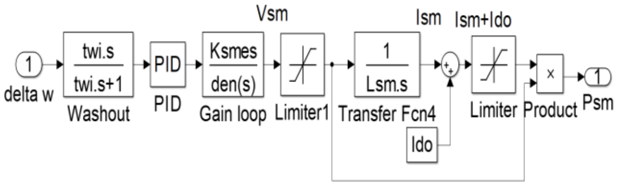

Figure 4. Block diagram of SMES-PID.

Capacitor Energy Storage (CES)

The working principle of CES is to store energy in the capacitor in the form of an electric field. CES components consist of a storage capacitor and a Power Comversion System (PCS). The storage capacitor consists of a number of discrete capacitors connected in parallel, with a capacitance (C). Dielectric capacitor bank and Leaking losses in the CES model are denoted by resistance (R) which is connected in parallel with the capacitor. The storage capacitors are connected to the network via a 12-pulse Power Conversion System (PCS). PCS components consist of an ac to dc rectifier and a dc to ac inverter. Figure 5 shows the CES scheme [19][20].

In the event of a converter failure, the thyristor bypass provides a current flow path (Id). The DC breaker allows the transfer of current energy (Id) to energize the resistor RD if the converter fails. Ignoring losses, the bridge stresses (Ed) are given at (8) and (9) [19][20].

$$E_d = 2E_{d0} cos\alpha - 2I_d R_D \quad (6)$$

$$E_{d0} = \frac{\left[E_{d\,max}^2 + E_{d\,min}^2\right]^{1/2}}{2} \quad (7)$$

More energy will be drawn by the capacitor because the capacitor voltage is too small and there are other disturbances that occur before the voltage returns to normal, this can cause intermittent control. To solve this problem, the lower limit for the capacitor voltage takes 30% of the rating value Ed0. Therefore, the mathematical representation can be described using (10) [19][20].

$$E_{d\,min} = 30E_{d0} \quad (8)$$

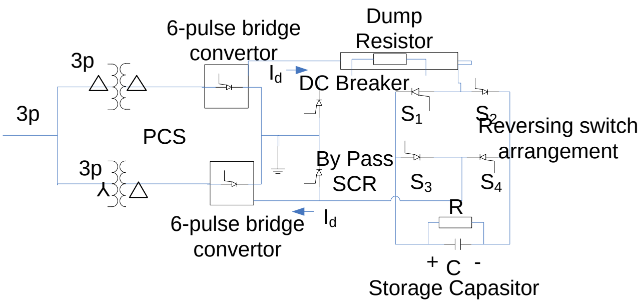

Figure 5. Schematic of capacitor Energy Storage

The operation of the capacitor is that the total energy absorbed is equal to the amount of energy drained. The capacitor is assumed to be of the specified value Ed0. The CES voltage must be found in its initial state as soon as possible to maintain system performance. Therefore, the negative feedback signal of the capacitor voltage deviation is very important to achieve the fast response of the CES. The CES block diagram is depicted in Figure 6 [20][21], where the capacitor voltage deviation (ΔEd) can be represented as given in (11) [20][21].

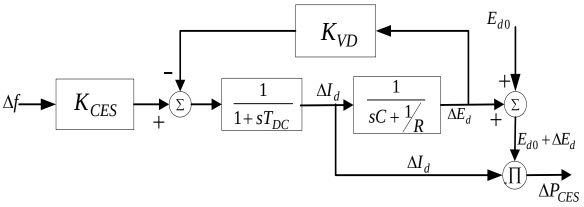

Figure 6. CES Model

$$AE_d = \left[\frac{1}{sC+{}^{1}/_{R}}\right]\Delta I_d \tag{9}$$

In addition, the CES power output injected into the system is shown in (12) [20][21].

$$\Delta P_{CES} = (E_{d0} + \Delta E_d)\Delta I_d \tag{10}$$

Method

The objective function used in this research is to optimize the Integral Time Absolute Error (ITAE) using the Bat Algorithm (BA) algorithm.

Overall Simulation

Based on (1) to (12), the system dynamics models are shown in Figure 7 and Figure 8. Figure 7 is a system test (micro hydro for frequency stability) with SMES and CES installed on the system. While Figure 8 is a model of the CES dynamic system on SIMULINK.

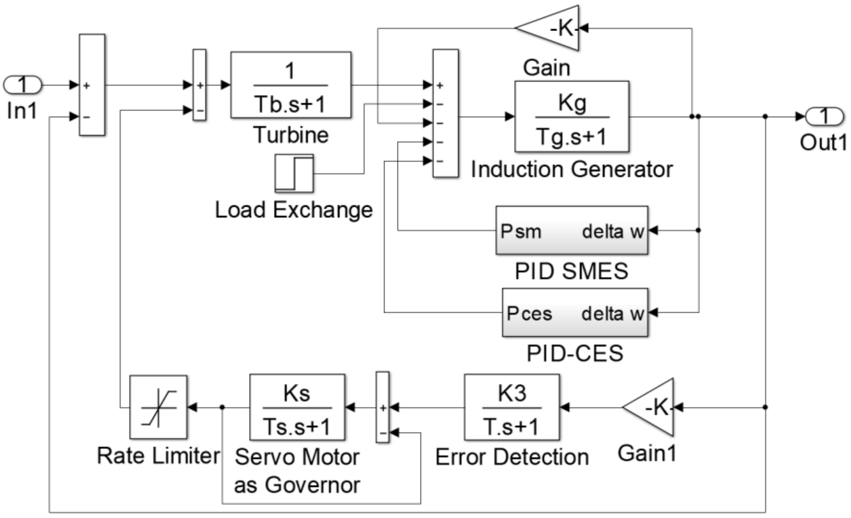

Figure 7. Simulink model

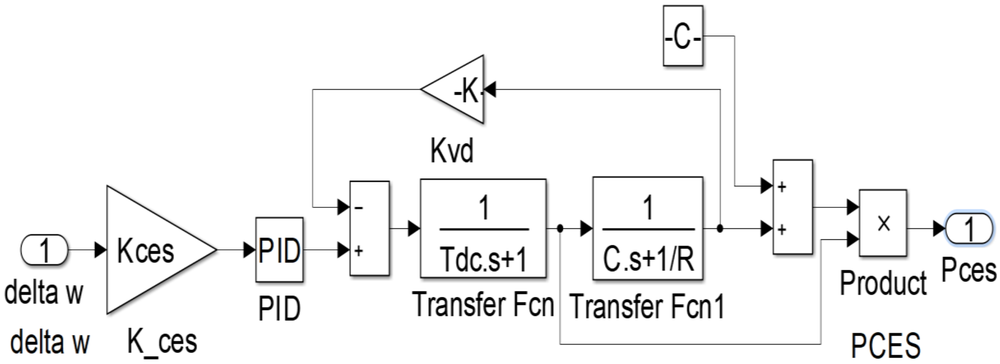

Figure 8. CES Model in Simulink

In this study, the system is modeled in a linear form. The optimized parameters are SMES and CES parameters.

Bat Algorithm

The main step of BA is to start from initialising the population of a group of bats, each of which is determined by the initial position as the initial solution. The population of a group of bats generates pulses and noise randomly and determines the frequency. During the iterative process/looping, the Bat will move from the initial solution to the best solution. After moving, if any bat finds a better solution, the Bat will update the pulse and noise emission levels. During the iteration process, the best solution is always updated. The iteration process is repeated until the stopping criteria, and the best solution criteria have been met. Then, the best solution is to solve the problem by going through this algorithm process [22].

The Bat Algorithm parameters used are shown in the following table. The working principle of Bat is optimising parameters within a predetermined limit. Therefore, bat parameters are shown in the following Table 1. The optimised parameters are Kces, Tdc, Kp, Ki, Kd, Tdc, Tw, dan Ksmes.

Objective Function

The objective function used is to optimize the Integral Time Absolute Error (ITAE), where BA will optimize the SMES and CES parameters so that the system will be more optimal, as indicated by the optimal micro hydro frequency as described in (13).

$$ITAE = \int_0^t t|\Delta\omega(t)|dt \qquad (13)$$

Where $\Delta\omega$ is the frequency oscillation of the microhydro, while t is the simulation period. The SMES parameters optimized by BA are Ksmes, Tdc, Tw, Kp, Ki and Kd, while the CES storage parameters are Kces, Tdc, Kp, Ki and Kd. Table 2 shows the SMES and CES parameters used in this study [23].

Table 1. BA Parameter

Parameter	Value
Population Size	35
Loudness	0,25
Pulse Rate	0,5
Alpha	0,7
Gamma	0,7
Minimum Frequency	0
Maximum Frequency	100
Iteration	50
Dimension	11

Table 2. Constraints

Parameters	Lower	Upper
CES		
Kces	80	90
Tdc	0.03	0.06
Kp	10	15
Ki	0.1	0.5
Kd	0	1
SMES		
Tdc	0.01	0.03
Tw	15	30
Ksmes	70	90
Kp	35	40
Ki	0	1
Kd	0	0.1

RESULTS AND DISCUSSION

This research discusses three analyses: governor response, turbine response, and micro hydro frequency response. The system is modelled using MATLAB / Simulink software. This research uses several micro hydro control system designs to test the system performance improvement according to the proposed method. Table 3 below shows the dynamic data of the micro hydro system. Table 4 shows the SMES and CES data optimised using the Bat Algorithm (BA) method.

Table 3. Dynamic data of the test system [24]

Parameter	Value
Tb	1
Kg	1
Tg	13,333
K1	5
K2	8,52
K3	0.004
T	0,02
Ts	0,1
Ks	2,5
Sg	40
pf	0,8
Vg	400/231
ω	1500
fg	50

Table 4. Optimal parameter of SMES and CES

Parameters	BA Result
CES	
Kces	89.5577
Tdc	0.6375
Kp	11.0724
Ki	1.0671
Kd	1.2012
SMES	
Tdc	0.6013
Tw	20.5028
Ksmes	81.3793
Kp	40.5466
Ki	1.5526
Kd	0.5974

Governor time domain response

In this section, the micro hydro governor response is analysed with interference in the form of load changes. Figure 9 shows the governor's response to several micro hydro control system scenarios. From this graph, it is obtained several characteristics of micro hydro governor response. Using a control system based on SMES-PID-CES-PID with the BA optimisation method, a minimum overshoot of the governor response is obtained.

Table 5 shows the overshoot of several micro hydro control system scenarios. From the analysis results obtained an optimal overshoot response using the SMES-PID-CES-PID. This is indicated by the minimum overshoot and faster settling time than other control scenarios.

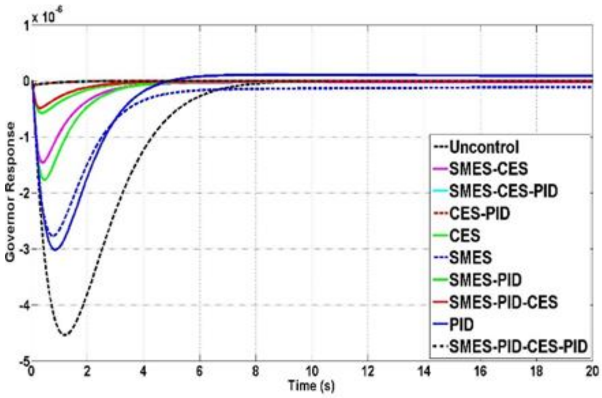

Figure 9. Respon Governor Micro Hydro

Table 5. Overshoot of governor

Cases	Overshoot
Uncontrolled	-4.541e-06
PID	-3.018e-06
CES	-1.766e-06
CES-PID	-1.304e-07
SMES	-2.767e-06
SMES-PID	-5.742e-07
SMES-CES	-1.459e-06
SMES-CES-PID	-1.283e-07
SMES-PID-CES	-4.862e-07
SMES-PID-CES-PID	-9.009e-08

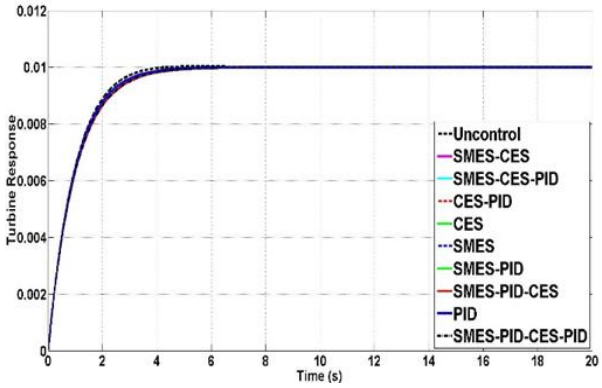

Figure 10. Turbine response under different scenarios

The increase in the performance of the micro hydro system can be seen from the response of the micro hydro system governor, as shown in Figure 9. With the optimal performance of the governor using the proposed method, the micro hydro turbine response will be more optimal. This is indicated by the faster turbine response when a load change occurs. This can be seen in Figure 10. It was using the SMES-PID-CES-PID control scenario results in a faster settling time than other control scenarios.

Frequency dynamic response

The next analysis is the frequency response of micro hydro. They review the micro hydro frequency response by providing interference in the form of load changes. Figure 11 compares the frequency response for several micro hydro control systems. The analysis results obtained the optimal micro hydro frequency performance using the SMES-PID-CES-PID control method. This is due to the addition of active power from SMES and CES.

Table 6 is the overshoot response of each analyzed model. The table shows that the system with SMES-PID and CES-PID produces a lower overshoot compared to other control system scenarios. SMES and CES can store and release active power from the system according to load conditions. For example, if the load increases, then SMES and CES will release (discharging) active power to the system, so that the system load is reduced (the system will experience lower overshoot). On the other hand, SMES and CES will store (charge) excess active power from the system when the load is reduced.

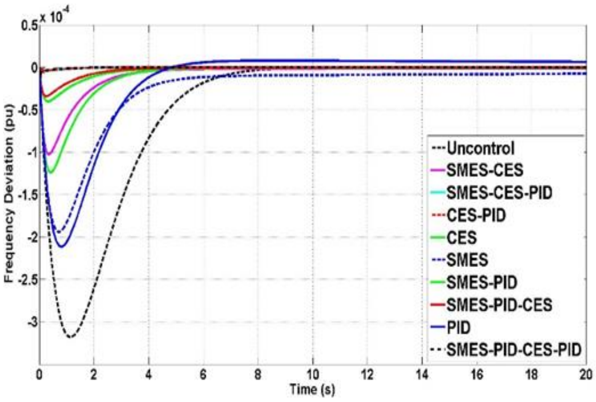

Figure 11. Frequency response under different scenarios

Table 6. Overshoot of Frequency

Cases	Overshoot
Uncontrolled	-0.000318
PID	-0.0002115
CES	-0.0001241
CES-PID	-1.445e-05
SMES	-0.0001939
SMES-PID	-4.038e-05
SMES-CES	-0.0001026
SMES-CES-PID	-1.432e-05
SMES-PID-CES	-3.43e-05
SMES-PID-CES-PID	--9.028e-06

CONCLUSION

This study proposes a method of increasing the frequency of the micro hydro system using a hybrid SMES and CES based on the Bat Algorithm. From the analysis results obtained, the addition of SMES and CES controls can improve the performance of the micro hydro frequency when a load changes. This is indicated by the minimum overshoot and faster settling time than other control schemes. Applying the Bat Algorithm method as an optimisation method for SMES and CES parameters can improve system performance. With optimal tuning, it results in increased micro hydro performance. The implementation of energy storage technology and intelligent optimisation can improve the performance of the power system. Battery Energy Storage (BES) technology can be implemented and combined with SMES and CES for further research.

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