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DESIGN A SUPPLEMENTARY SSR DAMPING CONTROLLER FOR STATCOM USING THE PARTICLE SWARM OPTIMIZATION METHOD

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Abstract- It is widely accepted that, series compensation of transmission lines results in increscent of power transfer capability. This kind of compensation may be led to adverse oscillations. The main objective of this work is to design a supplementary Sub-Synchronous Resonance (SSR) damping controller for STACOM using the Particle Swarm Optimization (PSO) method. For this purpose, the STATCOM is utilized and a supplementary controller is granted to its conventional controller. Furthermore, a performance index which is defined based on the system dynamics is implemented as an objective function to examine the potential of STATCOM in mitigating the oscillations. The effectiveness of the proposed controller is demonstrated through Fast Fourier Transform (FFT) analysis and time domain simulations conducted on IEEE Second Benchmark Model (SBM) combined with STATCOM.

Keywords: Particle Swarm Optimization (PSO), Sub-Synchronous Resonance Damping (SSRD), Single Machine Infinite Bus (SMIB), Second Benchmark Model (SBM).

I. INTRODUCTION

Power systems are needed to transmit the power over a long transmission lines in order to operate properly. Due to the increasing demand of the power, or in other way, due to increasing number of customers, it is necessary to enhance the power transfer capability of old transmission lines. Series capacitors are the most versatile devices for achieving to this goal [1]. However, if the compensated line is linked to the generator, the oscillatory modes of the generator shaft may be enticed. The result of such enticement will be an adverse oscillation with increasing amplitude and if it is not properly handled, it would be led to shaft failure [2].

Flexible AC Transmission Systems (FACTS) are one of the recent propositions to alleviate the SSR. So far, many countermeasures from FACTS family such as: TCSC [3], SSSC [4], and UPFC [5] have been employed in power systems in order to suppress the SSR. Amongst the available FACTS devices for SSR mitigation, STATCOM is the most adaptable one [6]. STATCOM is a shunt FACTS device which is generally used for voltage support or reactive compensation, but with an auxiliary controller it is capable of Low-Frequency Oscillation (LFO) and SSR damping [7, 8].

The most common type of damping controller is traditional lead-lag damping controller due to its ability to tune on-line and lack assurance of the stability by some adaptive or variable structure methods. Furthermore, it has shown that, the damping of oscillations will be improved with appropriate selection of controller parameters [9]. The main drawback of these controllers is the existence of more than one local optimum for lead-lag damping controllers. Hence, the conventional optimization techniques are not suitable for this problem. Thus, the heuristic methods which are widely implemented for the global optimization problems are developed [10-12]. Recently, the PSO method is appeared as a promising algorithm for managing the optimization problems. PSO is a population based stochastic optimization algorithm, prompted by social behavior of bird flocking or fish schooling [13-15]. PSO not only eliminates the deficiencies of other conventional optimization methods, but also, it utilizes a few parameters and is easy to implement.

In this paper, the PSO algorithm is utilized to design a robust SSR Damping controller (SSRD) for the STATCOM. The SSRD controller aims to adjust the reference value of STATCOM’s AC voltage in order to yield the proper damping of SSR. In order to better analyze the performance of proposed controller, a comparison is also adopted between conventional damping controller and proposed PSO controller. Simulation results and FFT analysis with Matlab verify the effectiveness of the proposed controller.

II. POWER SYSTEM UNDER STUDY

The structure of the power system that has been utilized for SSR study is shown in Figure 1. The IEEE Second Benchmark Model combined with STATCOM in bus 1 is considered for SSR analysis [16]. The system composed of a synchronous generator supplying power to an infinite bus via two parallel transmission lines. It is a Single Machine Infinite Bus (SMIB) power network that has two transmission lines, and one of those is compensated by a series capacitor.

A 600 MVA turbine-generator is connected to an infinite bus, and the rated line voltage is 500KV, while the rated frequency is 60Hz. The STATCOM is shunt connected to bus 1 by step up transformer. The mechanical system consists of four masses: a High Pressure turbine (HP), Low Pressure turbine (LP), the Generator (Ge) and rotating Exciter (EX). All masses are mechanically connected to each other by elastic shaft. The complete mechanical and electrical information for the study system are demonstrated in [16].

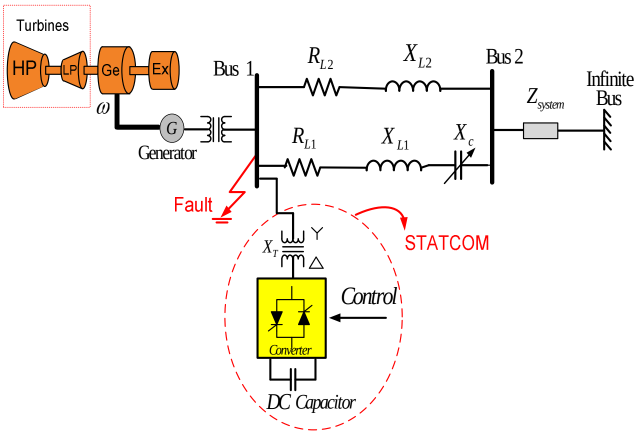

Figure 1. The IEEE second benchmark model combined with STATCOM for SSR analysis

For obtaining the oscillatory modes of the rotor shaft and consequently the sub-synchronous mode, the FFT analysis is performed on the system which is shown in Figure 1. The FFT plot of generator rotor speed in time interval of 0 to 1.5sec is described in Figure 2. Percentage of compensation (the proportion of series capacitive reactance to line reactance $=\frac{X_C}{X_{L1}}\times 100$ is set to 52% to excite the oscillatory mode of the generator rotor shaft. It is founded by FFT analysis with Matlab that, three modes exist in the rotor speed in this situation.

As shown in Figure 2, it can be deduced that, due to the chosen level of series compensation, the electrical resonance happens at 25.46 Hz. From FFT analysis of the mechanical system, the oscillatory modes of the generator shaft are 1.559, 25.46, 33.77 Hz. Furthermore, maximum destabilization is for 25.46 Hz mode, or in other way, the dominant mode which has sub-synchronous frequency is 25.46 Hz.

To verify how unfavorable this dominant mode is, the FFT analysis of the generator rotor speed is performed in time interval 1 to 9 sec with the time division of 2 sec. The results obtained for FFT analysis are displayed in Figure 3.

Referring to this figure, it can be observed that, as the time progresses, the dominant mode component increases significantly. So, if this amplification going to continue, the rotor shaft will be destroyed and there should be a controller for alleviating this adverse oscillatory component from rotor shaft in order to recover the power system from suffering.

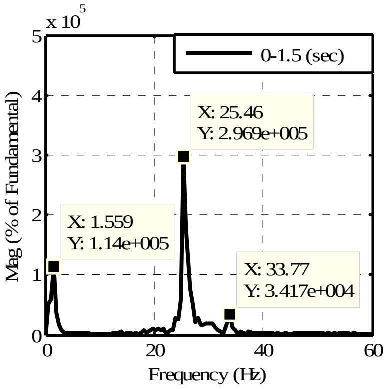

Figure 2. FFT analysis on generator rotor shaft in order to confirm the dominant mode

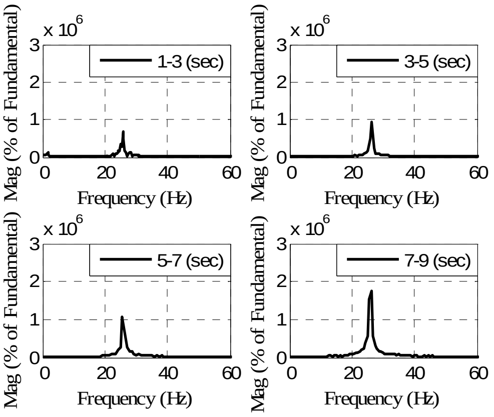

Figure 3. FFT analysis on ω of generator rotor speed with FLDC

III. DESCRIPTION OF STATCOM STRUCTURE

The basic structure of the STATCOM with its transformer is illustrated in Figure 1. The STATCOM is a power electronic based Synchronous Voltage Generator (SVG) that generates a three-phase voltage in synchronism with the transmission line voltage from a DC capacitor. Generally, it is connected to the transmission line by a coupling transformer. By controlling the output voltage magnitude of the STATCOM, the reactive power will be exchanged between STATCOM and the transmission system [6].

The STATCOM is based on the principle that regulates the voltage at its terminal with managing the amount of reactive power injected to or absorbed from the power system. When the system voltage is low, it generates a reactive power (capacitive mode) and in a similar manner, if the system voltage is high, it will absorb reactive power (inductive mode). The Voltage Source Converter (VSC) which is linked to secondary side of the coupling transformer contributes to perform the variations of the reactive power. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to create a voltage from a DC voltage source [6].

A. STATCOM Control

In order to control the power electronic switches, Sinusoidal Pulse Width Modulation (SPWM) is utilized. This signal is implemented to synthesize a sinusoidal wave form proportional in magnitude to the modulation gain k and shifted by the phase angle α. The supreme merit of pulse width modulation is that, both parameters k and α can be independently controlled. As the phase angle of the voltage on converter side is changed with respect to the phase angle of AC system voltage, the STATCOM will attempt to generate or absorb active power form the AC system. The exchanged active power will charge or discharge the internal DC capacitors [6].

The primary duties of a STATCOM are to control the AC line voltage V_S and the DC capacitor voltage V_{dc}. The AC voltage control is achieved by filtering out the second harmonic and the low frequencies of the AC voltage and then a lead-lag and PI controller are applied to the voltage error in order to attain the modulation phase shift α. The DC capacitor voltage error is put through a PI controller to provide the modulation index gain k. Figure 4 shows the control block of the STATCOM [6, 17].

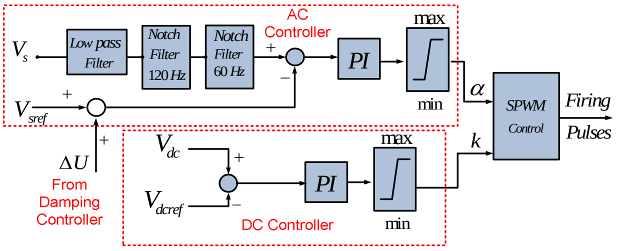

Figure 4. Block control of STATCOM

B. SSRD Controller Design

In this paper SSRD controller has been designed based on conventional lead-lag controllers. Conventional lead-lag controllers have been widely used in industry because of their simple structure, easy to design, robust performance in the linear system and low cost [9]. In this investigation, the aim is to mitigate the SSR. The speed deviation of generator rotor has been utilized as input signal of SSRD controller. As shown in Figure 5, $\Delta\omega$ [p.u] has been implemented as an additional signal to mitigate the unstable modes.

The auxiliary SSRD controller consists of five blocks: a washout filter, two phase compensator blocks, limiter block, and a gain block. The washout filter is used to prevent the controller from responding to the steady-state changes of the input signal. The phase compensator block presents the suitable lead-lag features so that to produce the damping torque. The limiter block tends to restrict the output of controller when it is going to decrease or increase from specific range. As shown in Figure 4, the output of the SSRD controller is added to the STATCOM's AC voltage regulator. The parameters T_W and limiter parameters are set manual but the other parameters will be optimized by PSO algorithm in order to yield the SSR suppression.

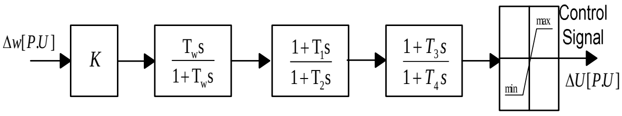

Figure 5. SSRD controller block diagram

IV. PSO ALGORITHM

PSO which is first developed by Kennedy and Eberhart in 1995, is a population based stochastic optimization method. It is inspired by social behavior of bird flocking or fish schooling [18]. It usually is implemented to improve the speed of the convergence and also to detect the global optimum value of the objective function. It can be utilized to solve many same problems as other kinds of algorithms such as Genetic Algorithm (GA). In comparison with GA, the PSO is easy to implement, needs fewer adjustable parameters, is suitable for the nature of the problem, and is easy for coding [9, 19, 20]. With consideration of these merits toward other methods, the researchers are convinced to use this method widely. The PSO is launched with some initial random particles and searches for the optimal point with updating the generations.

In the PSO algorithm, some simple entities which are named as particles are located in the search space of the problem or function. Each particle, at its current position, calculates the objective function and then determines its movement through the search space. The movement can be done by aggregating some facets of the history of each particle's current and the best positions by other particles or more members of the swarm with some random perturbations. When all the particles have been moved, the next iteration will be happened. At last, the swarm as a hole, just like school of fish which collectively searching for food, is likely to move toward an optimum of the objective function [21].

In the PSO technique, by dynamically regulating the velocity of each particle according to its own movement and the movement of the other particles, the trajectory of each individual in the search space is altered. The velocity vector and the position of ith particle in the D-dimensional search space can be expressed as: $V_i = (V_{i1}, V_{i2}, ...V_{id})$, $X_i = (X_{i1}, X_{i2}, ...X_{id})$, respectively. Consider a predefined objective function by the user; the best objective function obtained by ith particle at time (*pbest*), can be expressed as: $P_i = \left(P_{i1}, P_{i2}, ...P_{id}\right)$. Furthermore, the overall best value of the objective function obtained by the particles at time (*gbest*) is calculated through the algorithm. By using the following equations, the new velocity and new position of each particle can be achieved [13, 19]:

$$V_{id}(t) = W \times V_{id}(t-1) + C_1 r_1 \times (P_{id}(t-1) - X_{id}(t-1)) + C_2 r_2 \times \left(P_{gd}(t-1) - X_{id}(t-1)\right) \tag{1}$$

$$X_{id}(t) = X_{id}(t-1) + cV_{id}(t) \tag{2}$$

where, P_{id} and P_{gd} are *pbest* and *gbest*, respectively, C_1 and C_2 are positive constants which are responsible for alternation of the particle velocity toward *pbest* and *gbest*, and r_1 and r_2 are two random constants between 0 and 1. In order to balance the local and global searches and also to decrease the number of iterations, the W, or inertia weight is defined. The definition of inertia weight is expressed as [22]:

$$W = W_{\max} - \frac{W_{\max} - W_{\min}}{iter\_\max} iteration \qquad (3)$$

where, $iter\_\max$ is the maximum number of iterations and $iteration$ is the current number of iteration. The new inertia weight is updated through Equation (3), where $W_{\max}$ and $W_{\min}$ are initial and final weights. The flowchart of the proposed PSO algorithm for SSR study is shown in Figure 6.

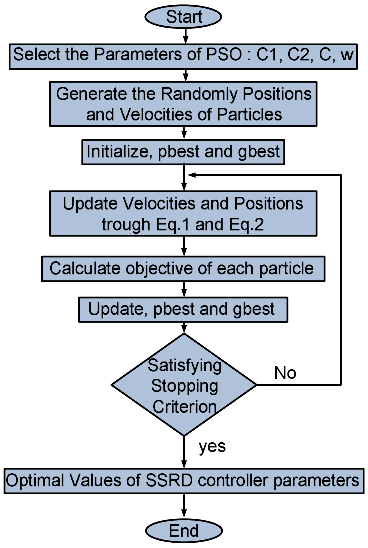

Figure 6. Flowchart of the PSO algorithm

A. Design of Damping Controller

In order to design the STATCOM's lead-lag damping controller, PSO technique is employed to determine the optimal parameters of the controller. In this study, an objective function which is come from speed deviation of rotor shaft is utilized in order to yield the appropriate output parameters for SSRD controller. The objective function is an integral of time multiplied absolute value of the speed deviation, and can be expressed by:

$$J = \int_0^{t_{sim}} t\left|\Delta\omega\right|.dt \qquad (4)$$

where, t_{sim} is the simulation time, and $\Delta\omega$ is the speed deviation of the rotor shaft in SMIB. The main aim of optimization is to minimize the objective function due to some constrains:

$$K^{\min} \le K \le K^{\max}$$
$$T_1^{\min} \le T_1 \le T_1^{\max} \quad , \quad T_2^{\min} \le T_2 \le T_2^{\max} \qquad (5)$$
$$T_3^{\min} \le T_3 \le T_3^{\max} \quad , \quad T_4^{\min} \le T_4 \le T_4^{\max}$$

The PSO algorithm searches for the optimal values of parameters above in range of: [0.001-200] for K and [0.001-3] for T_1, T_2, T_3, T_4. With implementing the time domain simulation model of the power system on simulation period, the objective function is computed and after reaching to specified criterion, the optimal parameters of the controller will be achieved. The parameters yielded from PSO algorithm are listed in Table 1.

Table 1. Parameters obtained from PSO algorithm

parameter	K	T_1	T_2	T_3	T_4
value	3.346	0.3439	0.001	2.639	0.001

B. Performance Index

In order to compare the results of proposed controller with conventional damping controller, a Performance Index is utilized based on the behavior of the power system. This index which is mainly consists of the integral of the time multiplied absolute value of the power system errors, can be defined as:

$$PI = t_{sim}\int_0^{tsim} t(\left|\Delta\omega\right| + \left|\Delta\delta\right| + \left|\Delta\omega_{LP}\right|)dt \qquad (6)$$

where, $\Delta\omega$ is the speed deviation of generator, $\Delta\delta$ is angle deviation, $\Delta\omega_{HP}$ is the speed deviation of high pressure turbine, and $\Delta\omega_{LP}$ is the speed deviation of low pressure turbine.

It should be noted that, the lower value of the PI, the better performance of controller will be guaranteed. Numerical results for two cases of study include conventional damping controller which is tuned by trial and error method and PSO based controller is listed in Table 2. It is observed that, the value of PI in a case of PSO based damping controller is much lower than its counterpart conventional damping controller. So, the PSO based damping controller operates efficiently than conventional damping controller. In order to validate the numerical results, time domain simulations will be carried out in the next section.

Table 2. PI index for proposed controllers

Controller	Conventional	PSO Based Controller
PI Value	1.6	0.43

Furthermore, the parameters of the proposed conventional damping controller which is optimized by trial and error method are included in Appendices.

V. SIMULATION RESULTS

In order to better assess the capability of the designed PSO based SSRD controller toward conventional controller, time-based simulation of the proposed system is utilized under disturbance. The three-phase to ground fault is occurred at time 0.1sec and lasts over 6 cycles. Figures 7, 8 and 9 show the generator rotor speed, the torque between Generator (Ge) and Low Pressure (LP) turbine and the torque between High Pressure (HP) and LP turbine, respectively. Where, the dashed line corresponds to the condition in which there is no SSRD controller in the system and the black solid line corresponds to the situation in which the STATCOM is enhanced with PSO based SSRD controller. Due to these figures, it is revealed that, the sub-synchronous oscillations are greatly removed when the SSRD controller operates. The STATCOM parameters are included in Appendices.

Figure 10 shows the algorithm convergence as a function of iteration number for the considered objective function. In general, the accuracy and the convergence ratio of the PSO algorithm is more convincing than other optimization algorithms as it is observed in Figure 10.

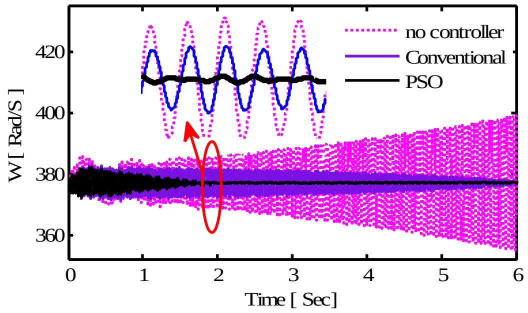

Figure 7. The generator rotor speed with conventional controller, PSO based controller and without damping controller

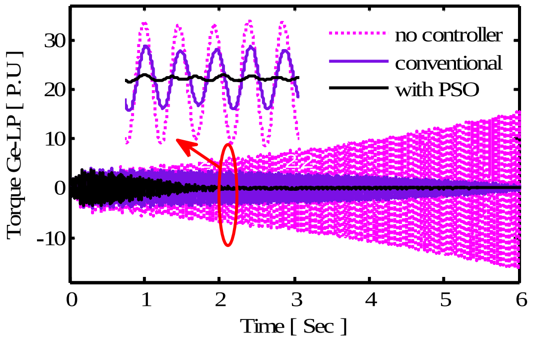

Figure 8. Torques between generator and low pressure turbine with conventional controller, PSO based controller, and without any controller

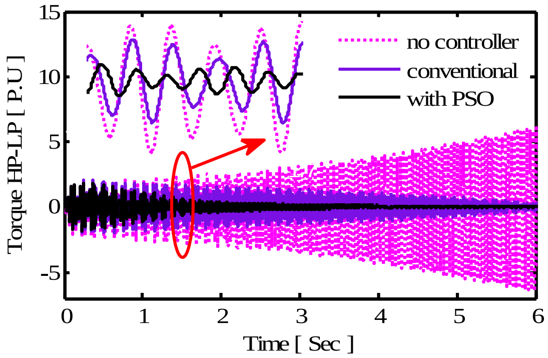

Figure 9. Torques between high pressure and low pressure turbine with conventional controller, PSO based controller and without any controller

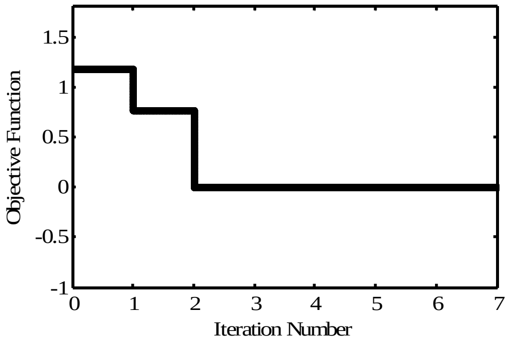

Figure 10. Convergence of objective function as a function of iteration

The FFT analysis on the generator rotor speed with PSO based SSRD controller on STATCOM is depicted in Figure 11. It is observed that, the dominant torsional mode with frequency of 25.46 Hz is diminishing as the time is going on and after 2 sec it is completely eliminated from the generator rotor speed, which verifies the effectiveness of the proposed SSRD controller based on PSO algorithm.

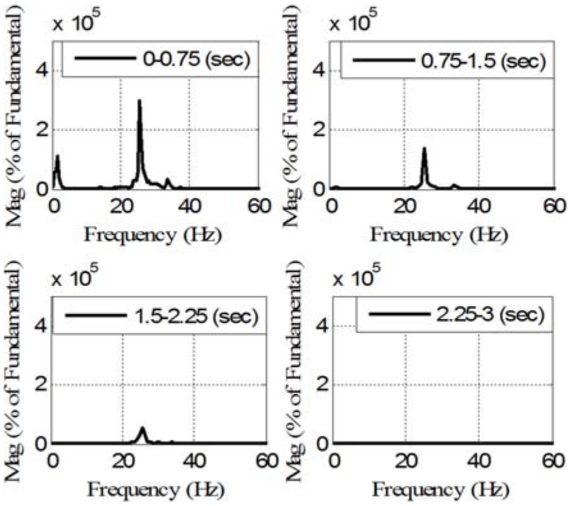

Figure 11. FFT analysis on rotor speed when STATCOM is enhanced with PSO based damping controller

V. CONCLUSIONS

In this paper, tuning of Sub-Synchronous Resonance Damping (SSRD) controller parameters is studied for a single machine system by using of PSO algorithm. First of all, the effect of series compensation of the transmission lines in SSR occurrence is studied with FFT analysis to obtain the oscillatory modes of the power system. The auxiliary lead-lag damping controller is designed and granted to STATCOM's conventional controller with the main aim of SSR suppression. The parameters of lead-lag damping controller are optimized through PSO algorithm by minimizing the objective function of the algorithm which is come from the behavior of the power system. The performance index is also defined to assess the superior performance of damping controllers. In comparison with GA the PSO can be implemented simply and the convergence speed is quick without too many parameters. Time domain simulations and FFT analysis with Matlab proved that, the proposed PSO based SSRD controller not only is capable of mitigating SSR greatly, but also it is superior than conventional damping controller.

APPENDICES

Appendix 1. STATCOM Data

Rated Power = 100 MVA, Rated Voltage = 26 KV, Frequency = 60 Hz, $X_{T(sh)} = 0.1$ p.u.,

Switching Frequency = 15 KHz.

Appendix 2. Auxiliary SSRD PSO Based Controller Data

$T_W = 2$, Max Limit = 10. Min Limit = -10.

Appendix 3. Auxiliary SSRD Conventional Controller Data

$T_W = 3.2$, Max Limit = 10. Min Limit = -10,

$T_1 = 0.42,\ T_2 = 0.14,\ T_3 = 2.9,\ T_4 = 0.01,\ k = 2.07$.

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