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Supplementary Signal of SVC for Damping Torsional Oscillation

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***Abstract*-A method is proposed in this paper to select supplementary signals for a static var compensator in IEEE first benchmark model. Different input output controllability analyses are used to assess the most appropriate supplementary signals for the static var compensator (SVC) for achieving effective damping of torsional oscillations. After placing the SVCs based on their primary functions, the most appropriate input signal for supplementary controller is also selected. The eigenvalues and hankel singular values of the system are computed incorporating various supplementary signals in the SVC for selecting the best supplementary signal.**

***Index Terms*—IEEE first bench-mark model, supplementary signals, RHP zeros, Eigen values, HSV.**

I. INTRODUCTION

Modern Power systems are highly complex, nonlinear and dynamic. Due to increasing transmission capacity and interconnections among different power systems, electromechanical oscillations restrict the steady-state power transfer limits and affect operational system economics and security. Therefore, these oscillations have become one of the main problems requiring solution in power system stability.

In recent years, there is an increasing interest in the application of SVCs to aid system damping by designing supplementary damping controller. There are various supplementary controllers the selection of appropriate stabilizing signals and effective tuning of such damping controls is an important consideration.

The relative gain array (RGA) and controllability and observability have been applied to investigate both, the problems of the best location and the selection of the input signals for multiple FACTS devices [1].Several papers also exist dealing with the combined application of controllability and observability using the singular value analysis for power system analysis [2, 3].

In [4] a detailed study on the use of a SVC for damping system oscillations, several factors including observability and controllability were considered, it was concluded that the most suitable auxiliary input signal for the SVC for damping improvement is the locally measured transmission line-current magnitude. This signal is also used in the study carried out in [5, 6]. Other studies, however, select locally measured active power [7, 8] or generator angular speed [9–11] as a stabilizing signal.

In the present paper, the most effective supplementary signal has been investigated based upon eigenvalue analysis of the linearized power system as given by the IEEE first benchmark model for SSR study. The criterion of RHP-zeros is used as the indicator for limiting the performance of the closed-loop system and the HSV as the indicator for controllability-observability.

Eigen values have been computed for the linearized system incorporating various supplementary signals such as Line reactive power auxiliary controller (LRPAC), Voltage angle auxiliary controller (VAAC), Active power auxiliary controller (APAC), Combined reactive power & voltage angle auxiliary controller (CRPVAAC) and Combined active power & voltage angle auxiliary controller (CAPVAAC).Hankel Singular Value(HSV) are computed for the same supplementary signals. It has been established that the combined active power & voltage angle auxiliary controller (CAPVAAC) is found to be most effective signal. Results obtained by eigenvalue analysis are corroborated by the Hankel Singular Value analysis.

This paper is organized as follows. Section II presents the study system used for investigation. Section III and IV gives details of various auxiliary controllers and concept of controllability, observability and Hankel Singular Values used for analysis. The time domain simulation is implemented and eigenvalues and HSV's are calculated for all auxiliary controllers under consideration and the results are analyzed in section IV. At last, the conclusions of the paper are given in section V.

II. SYSTEM MODELLING

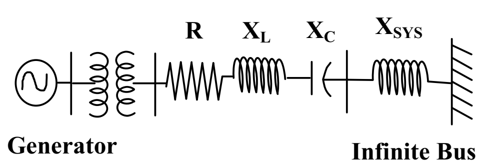

Fig. 1 IEEE First Benchmark Model for SSR study

The IEEE first bench-mark model is considered for analysis [12].The system consists of a single generator connected to an infinite bus through a single series compensated line as shown in Fig 1.The SVS is connected in the middle of line. It has been observed that SVS connected at the middle of the transmission line is not able to stabilize the oscillations produced due to the compensating capacitor presented towards load end, which limits the level of series compensation of line. The differential equations describing constituent subsystems, i.e. the generator, excitation, transmission, SVS and T-G set are summarized below:

Generator: In the detailed machine model [13-16] used here, the stator is represented by a dependent current source parallel with the inductance. The generator model includes the field winding 'f' and a damper winding 'h' along d-axis and two damper windings 'g' and 'k' along q-axis. Sub transient saliency and saturation neglected. The linearized state and output equation of the rotor circuit are as:

$$\dot{X}_R = [A_R]X_R + [B_{R1}]U_{R1} + [B_{R2}]U_{R2} + [B_{R3}]U_{R3} \quad (1)$$

$$Y_{R1} = [C_{R1}]\,X_R + [D_{R1}]\,U_{R1} \quad (2)$$

$$Y_{R2} = [C_{R2}]X_R + [D_{R2}]U_{R1} + [D_{R3}]U_{R2} + [D_{R4}]U_{R3} \quad (3)$$

where $X_R = \left[\Delta\psi_f \Delta\psi_h \Delta\psi_g \Delta\psi_k\right]^T \quad Y_{R1} = [\Delta I_D \Delta I_Q]^T$

$$Y_{R2} = [\Delta\dot{I}_D \Delta\dot{I}_Q]^T \quad U_{R2} = [\Delta V_F]^T \quad U_{R3} = [\Delta i_D \Delta i_Q]^T$$

Mechanical System: In the mechanical model detailed shaft torque dynamics has been considered for the analysis of torsional modes due to SSR. Viscous damping of each mass and shaft segment is represented by a dash pot damping. The state and output equations are given as follows:

$$\dot{X}_M = [A_M]X_M + [B_{M1}]U_{M1} + [B_{M2}]U_{M2} \quad Y_M = [C_M]X_M \quad (4)$$

where $X_M = [\Delta\delta_1 \Delta\delta_2 \Delta\delta_3 \Delta\delta_4 \Delta\delta_5 \Delta\delta_6 \Delta\omega_1 \Delta\omega_2 \Delta\omega_3 \Delta\omega_4 \Delta\omega_5 \Delta\omega_6]^T$

$$U_{M1} = [\Delta I_D \Delta I_Q]^T \quad U_{M2} = [\Delta i_D \Delta i_Q]^T \quad Y_M = [\Delta\delta_5 \Delta\omega_5]^T$$

Excitation System: The IEEE type-1 excitation system is used for the generator. The state and output equations of linearized IEEE type-1 excitation system model are derived as:

$$\dot{X}_E = [A_E]X_E + [B_E]U_E \quad Y_E = [C_E]X_E \quad (5)$$

where $X_E = [\Delta V_f \Delta V_s \Delta V_t]^T \quad U_E = \Delta V_g \quad Y_E = \Delta V_f$

Network Model: A single lumped pi circuit represents transmission line. The network is represented by its α axis equivalent circuit, which is identical with the positive sequence network. The governing equations of α axis pi network are derived as follows:

$$\dot{X}_N = [A_N]X_N + [B_{N1}]U_{N1} + [B_{N2}]U_{N2} + [B_{N3}]U_{N3} \quad (6)$$

$$Y_{N1} = [C_{N1}]X_N + [D_{N1}]U_{N1} + [D_{N2}]U_{N2} + [D_{N3}]U_{N3} \quad (7)$$

$$Y_{N2} = [C_{N2}]X_N \quad Y_{N3} = [C_{N3}]X_N \quad (8)$$

where $X_N = [\Delta i_{1D} \Delta i_{2D}\, \Delta i_{4D}\, \Delta i_D \Delta\dot{V}_{2D}\ \Delta\dot{V}_{3D}\ \Delta\dot{V}_{4D}\, \Delta\dot{V}_{5D}$
$\Delta i_{1Q}\ \Delta i_{2Q}\ \Delta i_{4Q}\, \Delta i_Q \Delta\dot{V}_{2Q} \Delta\dot{V}_{3Q} \Delta\dot{V}_{4Q}\ \Delta\dot{V}_{5Q}\,]$

$$Y_{N1} = [\Delta V_{gD}\, \Delta V_{gQ}]\ Y_{N2} = [\Delta i_D \Delta i_Q]\ Y_{N3} = [\Delta V_{3D}\, \Delta V_{3Q}]$$

$$U_{N1} = [\Delta i_{3D} \Delta i_{3Q}]\ U_{N2} = [\Delta I_D \Delta I_Q]\ U_{N3} = [\Delta\dot{I}_D \Delta\dot{I}_Q]$$

SVS System: The linearized state and output equations of the SVS model are obtained as:

$$\dot{X}_S = [A_S]X_S + [B_{S1}]U_{S1} + [B_{S2}]U_{S2} + [B_{S3}]U_{S3} \quad (9)$$

$$Y_S = [C_S]X_S + [D_S]U_{S1} \quad (10)$$

where $X_S = [\Delta i_{2D} \Delta i_{2Q} Z_1 Z_2 Z_3 \Delta B]^T \quad Y_S = [\Delta i_{2D} \Delta i_{2Q}]^T$

$$U_{S1} = [\Delta V_{2D} \Delta V_{2Q}]^T\ U_{S2} = [\Delta V_{ref}]\ \ U_{S3} = [\Delta V_F]$$

III. AUXILIARY CONTROL OF SVS

To effect the SVS control system, any general auxiliary signal U_C is implemented through the controller G(s). The state and output equations are given by

$$\dot{X}_C = [A_C]X_C + [B_C]U_C \qquad Y_C = [C_C]X_C + [D_C]U_C \quad (11)$$

where $X_C = Z_C$ and $Y_C = \Delta V_F$

A. *Line Reactive Power Auxiliary Controller*: The transmission, line reactive power entering SVS bus from the generator end is given by: $Q_3 = (V_{3D} i_{4Q} - V_{3Q} i_{4D})$

Linearization, gives the deviation in line reactive power ΔQ_3 which is selected as the auxiliary control signal. This is expressed in matrix notation as

$$U_C = [F_{CR}]X_R + [F_{CM}]X_M + [F_{CE}]X_E + [F_{CN}]X_N + [F_{CS}]X_S \quad (12)$$

where $U_c = [\Delta Q_2]$ and $F_{CR} = F_{CM} = F_{CE} = F_{CS} = 0$ (13)

where $[F_{CN}] = [0\ \ 0\ \ V_{3Q0}\ \ 0\ \ 0\ \ i_{Q0}\ \ 0\ \ 0\ \ 0\ \ 0\ \ V_{3D0}\ \ 0\ \ 0\ \ i_{D0}\ \ 0\ \ 0]$

B. *Voltage Angle Auxiliary Controller:* SVS bus angle is given by : $\boldsymbol{\theta_3 = \tan^{-1}\frac{V_{3Q}}{V_{3D}}}$

Linearization, gives $\Delta\theta_3 = \frac{d}{dt}\tan^{-1}\frac{V_{3Q}}{V_{3D}}$

This is expressed in matrix notation as

$$U_C = [F_{CR}]X_R + [F_{CM}]X_M + [F_{CE}]X_E + [F_{CN}]X_N + [F_{CS}]X_S$$

where $U_C = [\Delta\theta_3]$ and $F_{CR} = F_{CM} = F_{CE} = F_{CS} = 0$ (14)

where $[F_{CN}] = \left[0\ \ 0\ \ 0\ \ 0\ \ 0\ \ \frac{-V_{3Q}}{V_{30}^2}\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ \frac{V_{3D}}{V_{30}^2}\ \ 0\ \ 0\right]$

C. *Active Power Auxiliary Controller*: The line active power in existing SVS bus is given as: $\boldsymbol{P_3 = V_{3D}I_{4D} + V_{3Q}I_{4Q}}$

Linearization, gives

$$\Delta\dot{P}_3 = V_{3D}\Delta i_{4Q} + i_{4Q}\Delta V_{3D} + V_{3Q}\Delta i_{4D} + i_{4D}\Delta V_{3Q} \quad (15)$$

Equation (16) can be written in matrix form as

$$U_C = [F_{CR}]X_R + [F_{CM}]X_M + [F_{CE}]X_E + [F_{CN}]X_N + [F_{CS}]X_S$$

where $U_C = [\Delta P_3]$ and $F_{CR} = F_{CM} = F_{CE} = F_{CS} = 0$ (16)

$$[F_{CN}] = [0\ \ 0\ \ V_{3Q0}\ \ 0\ \ 0\ i_{4Q}\ 0\ \ 0\ \ 0\ \ 0\ \ V_{3D0}\ \ 0\ \ 0\ i_{4D0}\ 0\ \ 0]$$

The suffix 'o' indicates the corresponding operating point values.

D. *Combined Reactive Power And Voltage Angle Auxiliary Controller*: The auxiliary controller in this case comprises of a combination of reactive power and voltage angle.

$$\begin{bmatrix}\dot{X}_{C1}\\ \dot{X}_{C2}\end{bmatrix} = \begin{bmatrix}A_{C1} & 0\\ 0 & A_{C2}\end{bmatrix}\begin{bmatrix}X_{C1}\\ X_{C2}\end{bmatrix} + \begin{bmatrix}B_{C1} & 0\\ 0 & B_{C2}\end{bmatrix}\begin{bmatrix}U_{C1}\\ U_{C2}\end{bmatrix}$$

U_{C1} is auxiliary signal for reactive power and U_{C2} is auxiliary signal for voltage angle as derived earlier.

E. *Combined Active Power And Voltage Angle Auxiliary Controller*: U_{C1} is auxiliary signal for active power and U_{C2} is auxiliary signal for voltage angle as derived earlier.

IV. SELECTION OF INPUT SIGNALS

Right-Half Plane Zeroes (RHP-Zeros): For plant G different inputs-outputs will result in different zeros. Due to limiting performance of closed loop, inputs-outputs which produce the RHP zeros are not desired.

Considering the negative feedback system shown in Fig. 2 with plant G=z/p and a constant gain controller K=k, the closed-loop transfer function $Gc = \frac{KG}{1+KG} = \frac{kz}{p+kz} = k\frac{z_{cl}}{P_{cl}}$

From the above closed-loop transfer function, it is obvious that the locations of zeros are unchanged, while pole locations are changed by the feedback. The right-half plane zeros limit the achievable performance of a feedback loop. Also, from the root locus analysis, it can be seen that the locations of zeros are not changed by the feedback, but the pole locations are changed by the feedback. As the feedback gain decreases, the closed-loop poles will be moved to open-loop poles and as the feedback gain increases, the closed-loop poles will be moved from open-loop poles to open-loop zeros, which may lead to gain instability.

Thus, the selection of inputs-outputs should be carried out in a way that the closed-loop plant has a minimum number of the RHP-zeros, which are required not to lie within the closed-loop bandwidth [17-18].

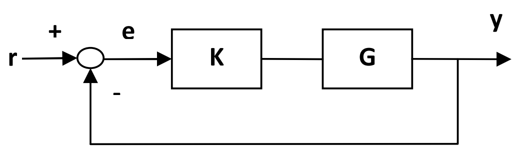

Fig. 2 Block diagram of a plant with feedback

Hankel Singular Values (HSV): Controllability and observability of a system play an important role in selecting input-output signals. In order to specify which combination of input-output contains more information about the system internal states, one possible approach is to evaluate observability and controllability indexes of the system.

A linear time invariant system can be defined as

$$G: \begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \quad (17)$$

Two possible ways to check that the above system is controllable are

- (A, B) is controllable if and only if matrix Φ , defined as Φ = [B AB A^2B …….A^{n-1}B] has full rank; where n is the number of states.
- (A,B) is controllable if and only if the controllability Gramian matrix defined as $P = \int_0^\infty e^{At} BB^T e^{A^T t} dt$ is positive definite, which has full rank n. Matrix P is the solution to the following Lyapunov equation: $P+PA^T+BB^T=0$

Also, there are two possible ways to check the observability of the above system (17):

- (A,C) is observable if and only if matrix Ψ,defined as $\Psi = \begin{bmatrix} C \\ CA \\ \cdot \\ . \\ CA^{n-1} \end{bmatrix}$ has full rank n.
- (A,C) is observable if and only if the observability Gramian matrix defined as $Q = \int_0^\infty e^{A^T t} BB^T e^{At} dt$

has full rank n and, thus, is positive definite. Matrix Q satisfies the following Lyapunov equation: $A^TQ+QA+C^TC=0$

The Hankel Singular Values (HSV) σ_i is an observability and controllability index, defined as

$\sigma_i = \sqrt{\lambda_i(PQ)}$, i=1,………, n

which reflects the joint controllability and observability of the states of a system where $\lambda_i(PQ)$ is the i^{th} eigenvalue of PQ.

Thus, for choosing input and output signals, the HSV can be calculated for each combination of inputs and outputs, the candidate with the largest HSV shows better controllability and observability properties. It means that this candidate can give more information about system internal states [18].

V. CASE STUDY

The study system consists of two 555 MVA synchronous generators represented by an equivalent 1110 MVA machine, supplying power to an infinite bus over a long transmission line. The midpoint connected SVS is rated at 300 MVA leading to 200 MVA lagging.

The objective of this study is to evaluate the comparative effectiveness of various auxiliary signals of SVS for enhancing the dynamic performance of series compensated transmission line in order to determine the most effective auxiliary control signal according to both eigenvalue and Hankel Singular Values.

The eigenvalue have been computed for the system with and without auxiliary controller incorporated in the SVS control system using pi circuit model of AC network.

For this system, since only one FACTS device is to be located in the system, the most effective signal is chosen based on the RHP zeros and HSV and is again validated by its eigenvalue. Once the FACTS device is placed in the system, the choices for stabilizing signal could be LRPAC, VAAC, APAC, CRPVAAC and CAPVAAC.

First, the RHP-zeros for the above candidates for the SVC are calculated. Table 1, we can see that no candidate encountered the RHP-zeros.

The eigenvalue have been computed for the system with and without auxiliary controllers incorporated in the SVS control system. The mechanical system is represented by a six spring mass model. The mechanical system damping is assumed to be zero in all cases to represent the worst damping conditions.

TABLE 1
RHP-Zeros for the 6 Stabilizing Signal Candidates

Stabilizing signal	RHP-zeros of system with SVC
LRPAC	No
VAAC	No
APAC	No
CRPVAAC	No
CAPVAAC	No

Table 2 presents the eigenvalues for P_G= 800W. When no auxiliary controller is incorporated, two unstable torsional modes, 4 and 1 are investigated in the system. When Line reactive power auxiliary controller is applied all modes are stabilized except mode 4. Similarly in Voltage angle auxiliary controller modes 4 and 1 are not stabilized but damping of all modes has improved more. When Active power auxiliary controller is applied still modes 4 and 1 are not stabilized. Stability of mode 4 is improved but mode 1 is not stabilized. Also when combined reactive power and voltage angle auxiliary controller is applied all modes except mode 4 are stabilized. When combined active power and voltage angle auxiliary controller is applied mode 4 and 1 are not stable.

Hankel singular values for the study system is been calculated with and without auxiliary controllers. It has been observed that combined active power and voltage angle auxiliary controller (CAPVAAC) is having highest HSV though mode 4 and 1 were not stable as other eigenvalues of the system are improved so its hankel value is largest. Voltage angle and line reactive power auxiliary controllers give approximately similar eigenvalues, but as LRPAC gives more stable modes so it is preferred over VAAC. After this lie the HSV of CRPVAAC and APAC.

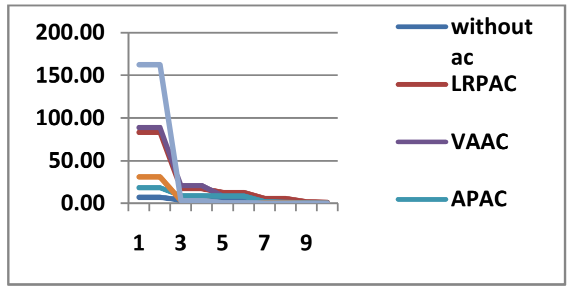

Fig. 3 HSV of the various stabilizing signals for the study system equipped with SVC

TABLE 2
Eigenvalue for P_G=800W

Auxiliary Controller Parameters	Without Auxiliary Controller	LRPAC		VAAC		APAC		CRPVAAC		CAPVAAC	
		K_B	-0.007	K_B	-0.4	K_B	-0.007	K_{B1}	-0.02	K_{B1}	-0.0006
								K_{B2}	-0.1	K_{B2}	-0.09
		T_1	0.08	T_1	0.02	T_1	0.0002	T_1	0.04	T_1	0.3
								T_2	0.006	T_2	0.009
		T_2	0.3	T_2	0.03	T_2	0.9	T_3	0.9	T_3	0.03
								T_4	0.07	T_4	0.009
Mode 5	-0.0000168±j 298.1005	- 0.0000159±j 298.100		-0.00001604±j 298.1005		-0.00001687±j 298.100		-0.00001228±j 298.10052		-0.0000164±j 298.1005	
Mode 4	0.0926317±j 202.72504	0.1066869±j 202.72348		0.08810859±j 202.740918		0.09269309±j 202.725		0.07936379±j 202.79351		0.0749548±j 202.7588	
Mode 3	-0.0233391±j 160.5074	-0.0115677±j 160.5123		-0.022956±j 160.49		-0.0233246±j 160.507		-0.01282852±j 160.48634		-0.0188476±j 160.4961	
Mode 2	-0.0032719±j 126.9624	-0.004086±j 126.966		-0.00030759±j 126.9598		-0.003274±j 126.9624		-0.00409±j 126.959019		-0.0000076±j 126.9608	
Mode 1	0.0691556±j 98.6655	-0.003463±j 98.671		0.11609±j 98.66514		0.06910924±j 98.665		-0.00031889±j 98.471582		0.107416±j 98.690916	
Mode 0	-0.0009931±j 5.873155	-1.033±j 6.0867		-1.04075±j 6.3294947		-1.01086188±j 5.8697		-1.653406± j6.36		-1.009586±j 5.97248	

TABLE 3
Hankel Singular Values

Number	Without Auxiliary Controller	LRPAC	BFAC	VAAC	APAC	CRPVAAC	CAPVAAC
1	7.09822151	83.07137136	124.56595004	88.67741433	18.24971653	31.10539027	162.20847838
2	7.09822079	83.06646710	124.56555974	88.67702395	18.24971448	31.10529787	162.20846203
3	3.98954988	17.35485905	24.038791264	20.73610497	8.689090944	3.072462392	3.0819811802
4	3.98934838	17.35485721	24.038789229	20.73610276	8.688673620	3.072462143	3.0819808458
5	3.79570049	12.85358823	18.261694118	8.518526755	8.483986337	4.649×10^{-01}	6.183×10^{-01}
6	3.79490467	12.85200681	18.259582124	8.516190814	8.481710906	4.649×10^{-01}	6.182×10^{-01}
7	9.594×10^{-01}	5.588994239	1.9023002963	1.740888172	1.958898263	1.947×10^{-01}	4.606×10^{-03}
8	5.641×10^{-01}	5.588636039	1.0092784295	1.009046154	1.146827855	1.947×10^{-01}	2.823×10^{-03}
9	4.475×10^{-01}	1.912464655	8.651×10^{-01}	8.936×10^{-01}	8.939×10^{-01}	3.585×10^{-03}	2.318×10^{-03}
10	2.416×10^{-01}	1.183228915	5.087×10^{-01}	4.893×10^{-01}	5.028×10^{-01}	1.759×10^{-03}	1.163×10^{-03}

So we can see that HSV plays a very significant role in deciding the best controller altogether with eigenvalues and RHP zeroes .Fig. 3 shows comparative analysis of HSV of system with various controllers.

VI. CONCLUSION

In this paper, the most effective supplementary signal has been derived with the help of both Eigen value analysis and Hankel Value analysis.

Six auxiliary controllers are applied for the system under consideration. RHP zeros are calculated for the linearized first bench mark model considering all seven auxiliary controllers. The simulation results are shown in table 1, 2 and 3. It is clear from the results of table 1, that there are no RHP zeros in any supplementary signal under consideration. The eigenvalues and hankel singular values are calculated for each supplementary signal to check the dynamic behavior of the system. Table 2 shows the eigenvalues for each mode considering one auxiliary controller at a time. The eigenvalues for each mode without controller is also shown in table 2.It is evident from the analysis of eigenvalues of mode 0 that the eigenvalue of this mode is to be improved for the stability of the system under low frequency oscillation. Further the dynamic behavior of the system is corroborated by calculating the hankel singular values of the system. Table 3 shows the hankel singular values calculated for each model of the system after applying the auxiliary controller. It is established from the simulation result of table 3 that overall performance of the system is improved by applying CAPVAAC. Fig. 3 shows the comparative study of auxiliary controllers on the basis of hankel singular values. The system performance is improved by applying CAPVAAC.

After comparing results from eigenvalues and hankel values we concluded that even though mode 4 and 1 are unstable but as HSV for CAPVAAC is highest hence it can give better overall system performance.

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