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Operational comparison of a new FACTS controller (RHFC) with other FACTS devices considering modified steady-state model

***Abstract**. In this paper, optimal power flow (OPF) is applied to optimally locate Rotary Hybrid Flow Controller (RHFC) and three other Flexible AC Transmission System (FACTS) devices to optimize the total fuel cost, power losses and system loadability as objective functions. The steady-state model of FACTS controllers are developed as a power injection model. A quantitative comparison of them are also investigated from economical and technical point of view. Simulations are performed on IEEE 14-bus and 118-bus test systems using Matlab and GAMS software environments.*

***Streszczenie.** W artykule opisano strategię optymalnego przepływu mocy OPF uzyskaną przez zastosowanie układu RHFC (Rptary Hybrid Flow Controller) oraz urządzeń systemu FACTS. Osiągnięto optymalne: koszt paliw, straty mocy i obciążalność. (**Zastosowanie nowego kontrolera RHFC do optymalizacji przepływu mocy w systemie energetycznym**)*

Keywords: Rotary Hybrid Flow Controller (RHFC), Flexible AC Transmission System (FACTS), Optimal Location, Power Injection Model
Słowa kluczowe: RHFC – rotary hybrid flow controler, FACTS, optymalizacja

Introduction

One of the most important and frequently used analysis for control and operation of power systems is the optimal power flow (OPF) program. An OPF program provides the most economical operating point that meets all the flow and voltage constraints related to power system performance. Flexible AC Transmission System (FACTS) controllers are characterized by their ability to provide dynamic control and compensation of voltage and power flow [1]. Optimal allocation of FACTS devices are playing an increasingly significant role in enhancement of system reliability and system dynamic behaviour. Many researches have been done on the optimal location of FACTS devices [2-4].

The objective of this paper is to provide appropriate models of FACTS controllers for optimization and present optimal placement and sizing of FACTS controllers for three objective functions including total fuel cost, power losses and system loadability. Also, a quantitative comparison of FACTS controllers are investigated from economical and technical point of view. In this paper, four typical FACTS devices have been investigated:Phase Shifting Transformer (PST), Unified Power Flow Controller (UPFC), Hybrid Flow Controller (HFC) and Rotary Hybrid Flow Controller (RHFC) as a new member of FACTS controllers.

PST is one of the most brilliant of FACTS controllers which can inject a series voltage to transmission line with controlled phase angle and magnitude. The PST is mainly composed of a set of mechanical switches that change the turn ratio of transformer. Due to slow function of mechanical switches, the PST is not suitable for dynamic studies [5-6].

UPFC is the most powerful and versatile FACTS controllers which is capable of providing active and reactive power control and voltage magnitude control [1]. The definitive and technical features of UPFC is discussed in [7]. UPFC usage is limited because of the cost considerations. So, the hybrid compensators are developed to the power system to use as a more cost effective devices and to enhance the capacity and flexibility of power transmission systems.

HFC that is introduced as a hybrid compensator is formed of a mechanically switched shunt capacitor, a mechanically switched phase-shifting transformer, and multimodule series-connected thyristor-switched capacitors and inductors [8]. Its operation is similar to that of UPFC with some advantages such as cost effectiveness. In the structure of HFC, the PST is less effective to control dynamic power flow and the function of phase shifting and voltage regulating are with some drawbacks. Therefore, RHFC has been introduced as a new member of FACTS controller in [9]. Structurally, an RHFC is composed a Rotary Phase-Shifting Transformer (RPST), a multimodule Thyristor-Switched Series Capacitor (TSSC), a multimodule Thyristor-Switched Series Reactor (TSSR) and a Mechanically-switched Shunt Capacitor (MSC). RPST is the main component of RHFC and the transformer characteristics of its windings prepare a rapid dynamic response and a low time constant.

The scope of this paper is focused on the static viewpoints of the optimal placement of FACTS devices. The power injetion model is used to solve OPF problem in IEEE 14-bus and 118-bus test systems. Furthermore, the optimization method is performed using Matlab and GAMS soft wares.
This paper is organized as follows: The modelling of FACTS controllers is studied in the next section. Then the OPF formulation including variables, objective functions and constraints are presented. After that, the OPF results for IEEE 14-bus and 118-bus test systems are reported. Optimal settings and the best position of FACTS controllers. are also determined in this section and final section explains conclusions.

Modeling of FACTS controllers

a) Modelling of RHFC

The RHFC consist of a RPST, a multimodule TSSC, a multimodule TSSR and a conventional MSC. A model of RHFC is shown in Fig. 1, where it is installed between buses i and j in a transmission line [9]. The RPST is the subsystem of RHFC which provides secondary three phase voltages on the rotor its module is proportional to that of primary stator voltages. The schematic of stator and rotor windings of RPST and the phase shifting angle of rotor windings shifted by angle β with respect to stator windings have been shown in Fig. 2.

Fig.1. RHFC structure

The basic function of RPST is to provide a continuous and rapid control of RHFC in both static and dynamic conditions. Also, the series transformer injects a controlled voltage in series with the transmission line and the shunt transformer provides input voltage to the RPST. In addition, for adjusting the line series reactance and preventing overflow TSSC and TSSR are augmented with RPST to form an RHFC.

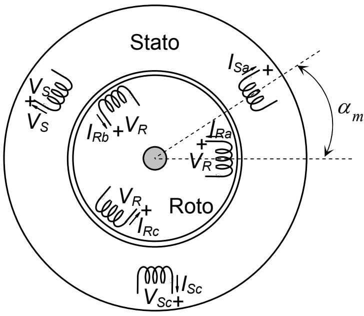

Fig.2. Stator and rotor windings of RPST

With reference to Fig. 3, the steady state condition of RHFC is presented by the following equations

(1)
$$P_{SS}=\frac{|V_i||V_j|}{X_{ij}}\Big(-(1+k\cos\beta)\sin(\theta_i-\theta_j)-k\sin\beta\cos(\theta_i-\theta_j)\Big)+\frac{|V_i||V_j|}{X_B}\sin(\theta_i-\theta_j)$$

(2)
$$Q_{SS}=\frac{|V_i|}{X_{ij}}\Big(|V_j|(1+k\cos\beta)\cos(\theta_i-\theta_j)-k\sin\beta\,|V_j|\sin(\theta_i-\theta_j)-|V_i|(1+2k\cos\beta+k^2)\Big)+\frac{|V_i|}{X_B}\Big(|V_i|-|V_j|\cos(\theta_i-\theta_j)\Big)$$

(3)
$$P_{SR}=-P_{SS}$$

(4)
$$Q_{SR}=\frac{|V_j|}{X_{ij}}\Big(|V_i|(1+k\cos\beta)\cos(\theta_i-\theta_j)-k\sin\beta\,|V_i|\sin(\theta_i-\theta_j)-|V_j|\Big)+\frac{|V_j|}{X_B}\Big(|V_j|-|V_i|\cos(\theta_i-\theta_j)\Big)+\frac{|V_j|^2}{X_{MSC}}$$

where

$$X_{ij}=X_{se}+\frac{X_{sh}k^2}{T_{sh}^2}+X_{rt}T_{se}^2+K_LX_L-K_CX_C+X_{line}$$

$k=T_{sh}T_{rt}T_{se}$; $\beta=\gamma+\sigma+\alpha$; $X_B=X_{se}+X_{line}$; α and T_{rt} are the RPST phase angle and transfer ratio between rotor windings and stator windings, respectively; σ and T_{se} are the RPST angle and transfer ratio between the primary and secondary voltage of the series transformer, respectively; γ and T_{sh} are the phase shifting angle and transfer ratio between high and low voltages of the shunt transformer, respectively; X_{line} is the transmission line reactance; X_{se} is the series transformer leakage reactance; coefficients K_L and K_C determine the amount of X_C and X_L in service. The power injection model of Fig. 3 is a general model that can be used for any shunt-series controllers [9].

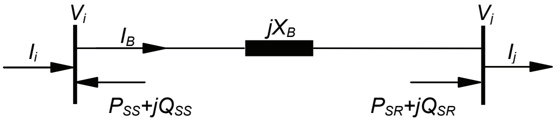

Fig.3. Power injection model of RHFC

b) Modeling of PST

The basic schematic of PST is shown in Fig. 4, which has been in existence for many years. PST includes two injecting and exciting transformers and mechanical switches. The PST connected to secondary windings of series and shunt transformers injects a voltage with a fixed phase to transmission network controlled by mechanical switches. Although the technology is relatively old, the PST proves to be a valuable means of control.

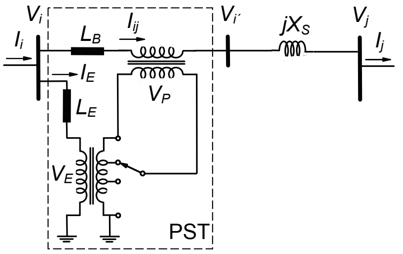

Fig.4. schematic diagram of PST.

The power injection model of Fig. 3 can be also used to the PST model where

$$Q_{SR}=\frac{|V_j|}{X_{ij}}\Big(|V_i|(1+k\cos\beta)\cos(\theta_i-\theta_j)-k\sin\beta\,|V_i|\sin(\theta_i-\theta_j)-|V_j|\Big)+\frac{|V_j|}{X_B}\Big(|V_j|-|V_i|\cos(\theta_i-\theta_j)\Big)+\frac{|V_j|^2}{X_{MSC}}$$

(5) $P_{ss}=-b_skV_iV_j\sin(\theta_i-\theta_j+\sigma)$

(6) $Q_{ss}=-b_skV_i^2(k+2\cos(\sigma))+b_skV_iV_j\cos(\theta_i-\theta_j+\sigma)$

(7) $P_{sr}=-P_{ss}$

(8) $Q_{sr}=b_skV_iV_j\cos(\theta_i-\theta_j+\sigma)$

c) Modelling of UPFC

The schematic diagram of UPFC which is capable to provide active and reactive power control and voltage magnitude control is presented in Fig. 5.

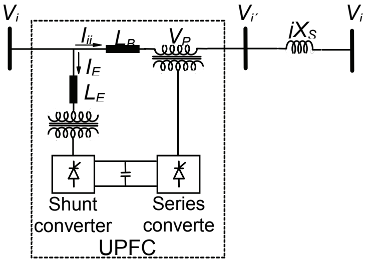

Fig.5. schematic diagram of UPFC

The modeling of UPFC is summarized with reference to the power injection model where

(9) $P_{ss}=-b_srV_iV_j\sin(\theta_i-\theta_j+\gamma)$

(10) $Q_{ss}=-b_srV_i^2(r+2\cos(\gamma))+b_srV_iV_j\cos(\theta_i-\theta_j+\gamma)$

(11) $P_{sr}=-P_{ss}$

(12) $Q_{sr}=+b_srV_iV_j\cos(\theta_i-\theta_j+\gamma)$

here r is the radius of the UPFC operating region and γ is the UPFC phase angle.

d) Modelling of HFC

The basic schematic of the HFC is shown in Fig. 5 [3,8].

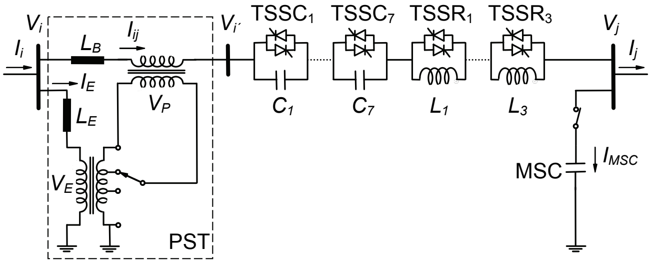

Fig.6. schematic diagram of HFC

The power injection model of the HFC is similar to that of RHFC shown in Fig.3 where

$$P_{ss} = \frac{V_i V_j}{X'_B}\sin(\theta_i - \theta_j) - \frac{V_i V_j}{X_{ij}} \left(k\cos(\theta_i - \theta_j) + \sin(\theta_i - \theta_j)\right) \tag{13}$$

$$Q_{ss} = \frac{V_i}{X'_B}\left(V_i - V_j\cos(\theta_i - \theta_j)\right) - \frac{V_i}{X_{ij}}\left(V_i(1+k^2) + kV_j\sin(\theta_i - \theta_j) - V_j\cos(\theta_i - \theta_j)\right) \tag{14}$$

$$P_{sr} = -P_{ss} \tag{15}$$

$$Q_{sr} = \frac{V_j}{X_{ij}}\left(V_i\cos(\theta_i - \theta_j) - kV_i\sin(\theta_i - \theta_j) - V_j\right) + \frac{V_j}{X'_B}\left(V_j - V_i\cos(\theta_i - \theta_j)\right) + K_m Y_{MSC} V_j^2 \tag{16}$$

here $X_{ij} = K_L X_L + k^2 X_E + X_B - K_C X_C + X_S$; X_E is the leakage reactance of exciting transformer; K_C, K_L and K_m determine the amount of X_C, X_L and Y_{MSC} in service, respectively; $X'_B = X_B + X_S$

Problem formulation

In the present text work, three objective functions including the system loadability, the total fuel cost and power losses are optimized. OPF problem can be expressed as the optimization of the objective function $f(x,y)$, subject to equality constraint $g(x,y)=0$ and inequality constraint $h(x,y)\geq 0$, where x and y are the vectors of independent and dependent variables and $g(x,y)$ denotes the power flow equations and $h(x,y)$ stands for state variable limits and physical constraints.

a) Objective Functions

a.1 The Total Fuel Cost

The most popular objective function is total fuel cost represented by a quadratic polynomial as follows:

$$F_1 = \sum_{i=1}^{NG} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \qquad (\$/\mathrm{h}) \tag{17}$$

where P_{Gi} is the active power output of i-th generator; NG is the total number of generators; a_i , b_i , c_i are the fuel cost coefficients of i-th generator .

a.2 The Real Power Losses

Considering power losses , it is useful to show the capability of the RHFC to reduce active power losses that can be expressed as

$$F_2 = P_{Loss}(x, y) = \sum_{l=1}^{N_l} P_l \tag{18}$$

where P_l is the real power losses at line-l and N_l is the number of transmission lines.

a.3 The System Loadability

The loadability of a network, namely its ability to transmit power is, in its most general form, a very complex quantity to model and to compute. The objective function can be defined by maximizing

$$F_3 = \rho(x, y) \tag{19}$$

and ρ can be obtained by assuming constant power factor at each load in the both real and reactive power balance equations as follows

$$P_G - \rho P_D = f_p(x, y) \tag{20}$$

$$Q_G - \rho Q_D = f_q(x, y) \tag{21}$$

where P_G and Q_G are the vectors of generators real and reactive power, respectively; P_D and Q_D are the vectors of loads real and reactive power, respectively; f_p and f_q are the vectors of real and reactive power flow equations, respectively.

Problem constraints

a) Equality Constraints

The power flow equations corresponding to both real and reactive powers must be satisfied as

$$P_{Gi} - P_{Di} - f_{Pi}(x,u) = 0 \tag{22}$$

$$Q_{Gi} - Q_{Di} - f_{Qi}(x,u) = 0 \tag{23}$$

here f_{Pi} and f_{Qi} are the real and reactive power flow equations at bus-i where the FACTS controller parameters are considered; P_{Gi} and Q_{Gi} are the generator real and reactive power at bus-i, respectively; P_{Di} and Q_{Di} are the load real and reactive power at bus-i, respectively.

b) Inequality Constraints

These constraints are related to upper and lower limits of each variable which must be satisfied. These constraints can be described mathematically as

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \;,\; i = 1,\ldots, NG \tag{24}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \;,\; i = 1,\ldots, NG \tag{25}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \;,\; i = 1,\ldots, N \tag{26}$$

$$S_{Li} \leq S_{Li}^{\max} \;,\; i = 1,\ldots, Nl \tag{27}$$

where N is the number of buses and Nl is the number of transmission lines.

$$\sigma^{\min} \leq \sigma \leq \sigma^{\max} \quad \text{for PST} \tag{28}$$

$$\left.\begin{aligned} r^{\min} &\leq r \leq r^{\max} \\ \gamma^{\min} &\leq \gamma \leq \gamma^{\max} \end{aligned}\right\} \quad \text{for UPFC} \tag{29}$$

$$(30)\quad \left.\begin{array}{l} k^{\min} \le k \le k^{\max} \\ 0 \le K_C \le K_C^{\max} \\ 0 \le K_L \le K_L^{\max} \\ 0 \le K_m \le K_m^{\max} \end{array}\right\} \quad \text{for RHFC and HFC}$$

In the RHFC device β is between -180 and 180.

Case Studies

The optimal location and sizing of RHFC, UPFC, HFC, and PST and their settings to minimize power losses and total fuel cost and maximize system loadability as objective functions, using Non Linear Programming (NLP) and Mixed Integer Non Linear Programming (MINLP) methods were discussed below. The optimal location of the FACTS controllers are implemented in GAMS. The determination of optimal location and sizing of FACTS devices are applied to the modified IEEE 14-bus and 118-bus test systems. The OPF results before and after installing the RHFC and a comparison of the RHFC power flow control characteristics with those of the UPFC, HFC and PST are prepared as follows.

a) IEEE 14-bus test system

FACTS devices are used to control power system operation indices in IEEE 30-bus system [10]. Simulations are carried out for three objective functions in Table 1.Total active and reactive power demands are 259MW and 73.5MVAr, respectively. According to Table 1.simulations for minimization of total fuel cost show the best results of total fuel cost, active and reactive power losses in the performance of HFC while the best performance in the minimization of RHFC sizing is observed.

In the second objective function, the result of UPFC is better than those of RHFC, HFC and PST in the active power losses and the result of PST is better than other FACTS devices in total fuel cost. In addition It is obvious that RHFC offers all technical features of other FACTS controllers. In the maximization of system loadability, the HFC gives the best performance in system loadability index. Also, a large improvement is observed in the minimization of RHFC sizing by optimal location of RHFC on line (6-13).

b) IEEE 118-bus test system

As shown in Table 2. IEEE 118-bus system [10] for the mentioned three objective functions is used to examine the integrated scheme of OPF with FACTS controllers. Total active and reactive power demands are 4242MW and 1438MVAr, respectively. In the minimization of fuel cost, the simulation results present the same results as the total fuel cost, active and reactive power losses in the performance of HFC and UPFC although their reactive power losses are larger than that of RHFC. The minimum size of FACTS devices belongs also to RHFC.

Table 1: Results of single objective optimization in IEEE 14-bus system

objective function	Parameters	Without FACTS	PST	HFC	RHFC	UPFC
F_1	Total Fuel Cost ($/h)	17278.804	17270.35	17216.64	17233.728	17218.71
	$\sum P_{loss}$ (MW)	1.7128	1.5987	0.8747	1.0908	0.902
	$\sum Q_{loss}$ (MVAr)	14.2818	13.4482	10.9443	11.6966	11.342
	Loadability Index	1	1.00	1.00	1.00	1.00
	FACTS Size (MVA)	-	28.00	65.30	27.525	59.96
	FACTS Location	-	Line 1-5	Line 1-5	Line 1-5	Line 1-5
	FACTS Settings	-	σ = 3.5311	K_C = 0 k= 0.124 K_m = 1 K_L= 0	K_C =4 k=0.0504 K_m =1 K_L=2 β=103.5	r = 0.135 γ = 77.102
F_2	$\sum P_{loss}$ (MW)	1.1280	1.0850	0.7658	0.8043	0.759
	Total Fuel Cost ($/h)	18186.618	18153.08	18397.97	18210.717	18379.88
	$\sum Q_{loss}$ (MVAr)	12.2680	11.2442	10.3518	11.6313	10.515
	Loadability Index	1	1.00	1.00	1.00	1.00
	FACTS Size (MVA)	-	25.44	61.13	27.735	56.65
	FACTS Location	-	Line 2-5	Line 2-4	Line 6-13	Line 2-4
	FACTS Settings	-	σ = 2.6611	K_C = 0 k= 0.090 K_m =1 K_L=0	K_C =0 k=0.0358 K_m =0 K_L=3 β=69.15	r = 0.105 γ = 72.774
F_3	Loadability Index	1.5565	1.5574	1.567	1.5595	1.566
	Total Fuel Cost ($/h)	30700.100	30700.100	30700.100	30700.100	30700.100
	$\sum P_{loss}$ (MW)	6.8621	6.6189	4.2433	6.1011	4.243
	$\sum Q_{loss}$ (MVAr)	30.8235	28.6694	21.0981	29.0982	21.098
	FACTS Size (MVA)	-	47.64	97.27	24.912	93.44
	FACTS Location	-	Line 1-5	Line 2-3	Line 6-13	Line 2-3
	FACTS Settings	-	σ = 6.1217	K_C =5 k= 0.142 K_m =1 K_L=0	K_C =7 k=0.0169 K_m =1 K_L=0 β=136.1	r = 0.184 γ = 88.496

If the power losses is chosen as an objective function, the results show that the performance of UPFC is better than that of other FACTS controllers while a considerable reduction in sizing of HFC is observed compared to other FACTS devices. It should be noted that internal losses are ignored in UPFC.

Table 2: Results of single objective optimization in IEEE 118-bus system

objective function	Parameters	Without FACTS	PST	HFC	RHFC	UPFC
F_1	Total Fuel Cost ($/h)	129660.997	129467.56	129346.92	129395.973	129346.92
	$\sum P_{loss}$ (MW)	77.4079	73.2224	70.504	71.4080	70.504
	$\sum Q_{loss}$ (MVAr)	507.2500	479.4020	480.755	469.2732	480.755
	Loadability Index	1.00	1.00	1.00	1.00	1.00
	FACTS Size (MVA)	-	200	200	145.864	200
	FACTS Location	-	Line 25-27	Line 69-75	Line 25-27	Line 69-75
	FACTS Settings	-	σ =17.5429	K_C =0 k=0.229 K_m =1 K_L=0	K_C =7 k=0.2282 K_m =0 K_L=0 β=81.342	r =0.253 γ = 82.301
F_2	$\sum P_{loss}$ (MW)	9.2476	8.9374	7.8041	7.8019	7.801
	Total Fuel Cost ($/h)	166390.383	165970.68	166554.78	166554.076	166554.06
	$\sum Q_{loss}$ (MVAr)	69.3829	68.6637	64.0889	64.0764	64.074
	Loadability Index	1.00	1.00	1.00	1.00	1.00
	FACTS Size (MVA)	-	189.57	136.22	157.182	136.58
	FACTS Location	-	Line 89-90	Line 80-96	Line 80-96	Line 80-96
	FACTS Settings	-	σ =-19.4036	K_C =0 k=0.224 K_m =1 K_L=0	K_C =7 k=0.3805 K_m =0 K_L=0 β=76.358	r =0.237 γ =76.373
F_3	Loadability Index	2.0385	2.2836	2.284	2.2844	2.2844
	Total Fuel Cost ($/h)	347709.059	417113.21	417113.21	417113.206	417113.21
	$\sum P_{loss}$ (MW)	205.1381	278.9912	276.0178	275.9037	275.688
	$\sum Q_{loss}$ (MVAr)	1165.5570	1556.1691	1544.1271	1543.6369	1543.099
	FACTS Size (MVA)	-	200	200	200	200
	FACTS Location	-	Line 69-75	Line 69-75	Line 69-75	Line 69-75
	FACTS Settings	-	σ =14.2752	K_C =7 k=0.124 K_m =2 K_L=1	K_C =7 k=0.1309 K_m =2 K_L=0 β=62.614	r =0.260 γ = 54.608

According to Table2, simulations for maximization of the system loadability show the same result of the loadability index for RHFC and UPFC. Also, In the last objective function, with the optimal placement of RHFC on line (69-79), the result of total fuel cost, is better than that of PST, UPFC and HFC.

Conclusions

This paper made an attempt to develop steady-state power flow model for optimal location of RHFC as a new hybrid compensator and also other FACTS devices to improve the power system operation. The modified power injection model, suitable for the power flow analysis of RHFC, HFC, UPFC and PST is utilized. The optimization problem were carried out on three objective functions namely total fuel cost, power losses and the system loadability. Furthermore, the optimization model is performed on IEEE 14-bus and 118-bus test systems using GAMS software. The various results shown in the tables compare the scenario without FACTS and with RHFC, HFC, UPFC and PST. The results show the effectiveness of optimal location and sizing of FACTS controllers in a transmission system. Also, simulation results illustrate that RHFC not only offers all technical features of other FACTS controllers but also, provides additional opportunities to control power flow with some advantages like fast response with continuous control and wide spread control range.

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