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A Multi-Objective Hybrid Heuristic Approach for Optimal Setting of FACTS Devices in Deregulated Power System

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Abstract: *Improvement of power system performance in terms of increased voltage profile and decreased transmission loss is becoming one of the challenging tasks to the system operators under open access environment. Apart from traditional power flow controlling devices, use of Flexible AC Transmission System (FACTS) devices can give an attractive solution for the operation and control of deregulated power system. The type, size, location and number of FACTS devices are to be optimized appropriately in order to get the targeted benefits. In this paper, two FACTS devices, TCPST and IPFC are selected to obtain the required performance. To search the optimal location and optimal rating of the selected FACTS devices, a hybrid algorithm which formulated with PSO and GSA is proposed. At the first step, the optimization problem is solved for finding the optimal location of FACTS devices using PSO with an objective of voltage profile maximization and later GSA is implemented to optimize their parameters with an objective of transmission loss minimization. The proposed method is implemented on IEEE 30-bus test system and from the simulation results it can be proved that this technique is well suited for real-time application.*

Keywords: *Deregulated power system, open access, TCPST, IPFC, PSO-GSA*

I. Introduction

The practical limitations to expansion and ever increasing electricity demand are causing to operate transmission system at its bottleneck under competitive environment in deregulated power system. In addition, the randomness in power injection and withdrawals with the strategic behavior of market participants are further causing to decrease the security margin of transmission system. Under this scenario, the primary objectives to introduce Flexible AC Transmission System (FACTS) devices are redefined by many researchers during last decade. Some of the major areas focused with FACTS devices are like security margin enhancement [1-3], stability enhancement [4-10], reliability management [11], system performance improvement [12-19], congestion management [20-24] and electricity market economic efficiency maximization [25-30] etc.

As per the controlling attribute in power system, the type, size, location, number etc. are required to optimize very precisely. Many researchers have attempted to solve this problem by heuristic algorithms due to their adoptability for multi-objective complex problems. Using Genetic Algorithm (GA), the optimal location and number of thyristor-controlled phase shifters are optimized in [31, 32]. In [33], hybrid TS/SA approach has been proposed to solve OPF problem incorporating FACTS devices. An evolutionary algorithm based evolution strategies (ES) technique is proposed to maximize system loadability via optimizing type of FACTS device, their location and settings [34]. Similarly, the ABC algorithm and PSO algorithm application for optimizing IPFC location can be found [35, 36]. On other side, the conventional approach like mixed-integer nonlinear programming (MINLP) is adopted to find the optimal setting of FACTS devices used in the optimal power-flow problem. [37].It is worthwhile to notify the role of heuristic algorithms used to solve in all these complex problems.

The objective of this paper is not only to resolve multi-objective optimization problem but also to investigate the effectiveness with the use of FACTS devices for the improvement of the performance of transmission system. This is an extension of our existing works [38] under open access environment. Under open access, the bilateral or multilateral transactions are executed with an assumption of unconstrained transmission system. With this new generation and loading levels, the ability of various FACTS devices for the improvement of the transmission system performance is analyzed. Two FACTS devices, TCPST and IPFC devices are used in this work. To identify the most suitable locations, the Particle Swarm Optimization (PSO) is applied first. Later, the Gravitational Search Algorithm (GSA) is implemented to find the optimal parameters of the FACTS devices. The overall voltage deviation index (VDI) is considered while optimizing the location and the transmission loss is considered while optimizing the parameters of FACTS devices.

This paper is arranged as follows: section 1 gives introduction, section 2 shows the power injection modeling of various FACTS devices. Section 3 explains the objective function in the necessary mathematical equations. In section 4, the proposed hybrid algorithm is explained briefly. Section 5 deals with various case studies on standard IEEE test systems and section 6 concludes the paper.

II. Modeling of FACTS Devices

2.1. Thyristor Controller Phase Shift Transformer

As far as the static modeling is concerned, the power injection equations are as follows:

$$P_{inj,i} = r\frac{1}{X_{se}}V_iV_j\sin\left(\delta_i-\delta_j+\phi_{tcpst}\right)$$

$$Q_{inj,i} = r^2\frac{1}{X_{se}}V_i^2 - r\frac{1}{X_{se}}V_iV_j\cos\left(\delta_i-\delta_j+\phi_{tcpst}\right)$$

$$P_{inj,j} = -P_{inj,i}$$

$$Q_{inj,j} = -r\frac{1}{X_{se}}V_iV_j\cos\left(\delta_i-\delta_j+\phi_{tcpst}\right)$$

where, $\tan\phi_{tcpst}$ is the phase angle adjustment by TCPST between $\left[+\frac{\pi}{2},-\frac{\pi}{2}\right]$, *r* is the ratio between the magnitude of the induced series voltage and magnitude of the i^{th} bus voltage. It is variable in the range $\left[0,r_{\max}\right]$, δ_i and δ_j are the load angles of buses $i,\ j$ respectively. In addition, $X_{se}=x_{se}+n^2x_{sh}$, where x_{se} and x_{sh} are the series and shunt reactances of transmission line/transformer and n is the variable of the phase shift angle. The detailed information can be found in [39].

2.2. Interline Power Flow Controller

By assuming IPFC location between buses *i, j* and *k*, the power injections are as follows [15, 16].

$$P_{inj,i} = \sum_{n=j,k} V_i\,V_{se_{in}}b_{in}\sin\left(\delta_i-\delta_{se_{in}}\right)$$

$$Q_{inj,i} = -\sum_{n=j,k} V_i\,V_{se_{in}}b_{in}\cos\left(\delta_i-\delta_{se_{in}}\right)$$

$$P_{inj,n} = V_j\,V_{se_{in}}b_{in}\sin\left(\delta_j-\delta_{se_{in}}\right) \qquad n=j,k$$

$$Q_{inj,n} = -V_j\,V_{se_{in}}b_{in}\cos\left(\delta_j-\delta_{se_{in}}\right) \quad n=j,k$$

Here $V_{se_{in}}$ and $\delta_{se_{in}}$ are the magnitude and angle of series injected voltage source.

III. Problem Formulation

The transmission system performance can be mathematically formulated in terms of two terms: voltage deviation of the system, $f_1(x,u)$, and transmission losses, $f_2(x,u)$.

Therefore the major objective function can be defined as:

$$F(x,u)=\left[f_1(x,u),\ f_2(x,u)\right]$$

The first objective is to optimize the overall system voltage profile i.e., minimize the voltage deviation at load buses, which can be defined as

$$f_1(x,u)=VDI(x,u)=\sum_{i=1}^{NLB}\left|V_i-V_i^{ref}\right|^2$$

where *NBL* is the number of load buses, V_i^{ref} is the pre-specified reference magnitude at i^{th} load bus, which usually with magnitude of 1.0 p.u. The second objective is to minimize the total real power loss of the lines, which is written as:

$$f_2(x,u)=P_{loss}(x,u)=\sum_{i=1}^{NL}P_{i,loss}$$

where $P_{i,loss}$ is the real power loss in transmission line *i*, and NL is the total number of transmission lines.

In both the objective functions, ***x*** denotes the vector of dependent variables such as slack bus power P_{G1}, generator reactive power outputs Q_G, load bus voltages V_L and apparent power flows in transmission lines S_L. Therefore x can be defined as:

$$x^T=\left[P_{G1},Q_{G1},...Q_{NGB},V_{L1},...V_{NLB},S_{L1},...S_{NL}\right]$$

where NGB is the number of generator buses.

Similarly, ***u*** denotes the vector of control variables such as generator bus voltages V_G, location of FACTS devices *L*, and real and reactive power injections P_{inj} & Q_{inj} at FACTS device incident buses *i, j* respectively. Therefore ***u*** can be expressed as:

$$u^T = \left[V_{G1},...V_{NGB}, L_1,...L_{NL}, P_{inj,i}, Q_{inj,i}, P_{inj,j}, Q_{inj,j}\right]$$

As per the type of FACTS device, the power injections again controlled with their respective controlling parameters.

a) Equality constraints

The equality constraints which are the real and reactive power balance equations for all the buses except buses *p* and *q* with UPFC are shown in the following equations.

$$P_i = P_{g,i} - P_{d,i} = \sum_{k=1}^{NB} |V_i||V_k||Y_{ik}|\cos\left(\theta_{ik} - \delta_i + \delta_j\right)$$

$$Q_i = Q_{g,i} - Q_{d,i} = -\sum_{k=1}^{NB} |V_i||V_k||Y_{ik}|\sin\left(\theta_{ik} - \delta_i + \delta_j\right) \qquad i = 1, 2, ..., NB \text{ ; but } i \ne p, q$$

For buses *p* and *q*, the equality constraints can be written as

$$P_p = P_{g,p} - P_{d,p} = \sum_{k=1}^{NB} |V_p||V_k||Y_{pk}|\cos\left(\theta_{pk} - \delta_p + \delta_j\right) - P_{p,inj}$$

$$Q_p = Q_{g,p} - Q_{d,p} = -\sum_{k=1}^{NB} |V_p||V_k||Y_{pk}|\sin\left(\theta_{pk} - \delta_p + \delta_j\right) - Q_{p,inj}$$

$$P_q = P_{g,q} - P_{d,q} = \sum_{k=1}^{NB} |V_q||V_k||Y_{qk}|\cos\left(\theta_{qk} - \delta_q + \delta_j\right) + P_{q,inj}$$

$$Q_q = Q_{g,q} - Q_{d,q} = -\sum_{k=1}^{NB} |V_q||V_k||Y_{qk}|\sin\left(\theta_{qk} - \delta_q + \delta_j\right) + Q_{q,inj}$$

b) Inequality constraints

- Real power generation limits: The upper and lower limit of the real power generated by the generators can be shown as

$$P_{g,i}^{\min} \le P_{g,i} \le P_{g,i}^{\max}, \qquad i = 1, 2, ..., NG$$

- Reactive power generation limits: The upper and lower limit of the reactive power can be shown as

$$Q_{g,i}^{\min} \le Q_{g,i} \le Q_{g,i}^{\max}, \qquad i = 1, 2, ..., NG$$

- Voltage limits: The upper and lower limit of the bus voltage magnitude can be shown as

$$\left|V_i^{\min}\right| \le |V_i| \le \left|V_i^{\max}\right|, \qquad i = 1, 2, ..., NG$$

- Phase angle limits: The upper and lower limits on the bus voltage phase angle can be shown as

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max}, \qquad i = 1, 2, ..., NG$$

- Tap-Changers limits: The upper and lower limits on the tap positions in tap-changing transformer lines can be shown as

$$a_i^{\min} \le a_i \le a_i^{\max}, \qquad i = 1, 2, ..., NTCL$$

- MVAr injection limits: The upper and lower limits on the MVAr injections at voltage controlled buses can be shown as

$$Q_{inj,i}^{\min} \le Q_{inj,i} \le Q_{inj,i}^{\max}, \qquad i = 1, 2, ..., NVCB$$

- Line flow limits: The maximum MVA power flow in a transmission line can be shown as

$$|S_l| \le \left|S_l^{\max}\right|, \quad l = 1, 2, ..., NL$$

IV. Proposed Hybrid Approach

The hybrid algorithm adopted here is similar to our previous works and the detailed algorithm can be found [38]. The pseudo code of the procedure involved in PSO-GSA is as follows:

PSO for Optimal Location	**GSA for Optimal Parameters**
1. For each particle i. Initialize particle, End Do	1. Search space identification, t=0; 2. Random initialization, *Xi(t);* For *i=1, ..., N*

```
     2. For each particle
i.   Calculate fitness value
     If it is better than the best fitness value
     (pBest) in history
      iii. Set current value as the new pBest
         End
     3. Choose the particle with the best fitness
     value of all the particles as the gBest
     4. For each particle
i.   Calculate velocity
i.   Update position
     End - while maximum iterations or
     minimum error criteria is not attained.
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```
3. Fitness evaluation of objects;
4. Update the parameters of G, best,
   worst and M;
     For i=1, ..., N
5. Calculation of the force on each
   object;
6. Calculation of the acceleration and the
   velocity of each object;
7. Update the position of the agents by
   (4) to yield Xi(t+1);    t=t+1;
8. Repeat steps 3 to 7 until the stop
   criteria is reached;
9. End
```

V. Case Studies

The GSA-PSO algorithm is applied for optimal placement of each FACTS device on the IEEE 30-bus test system. The real load of the system is 283.4 MW. We have allocated 37.7615 MW for generator 2 and the rest of load is allocated to generator 1. Since the test system has consisting of 6 generator buses and 21 load buses. Hence each generator can treat as source bus and similarly each load bus can be like a sink bus in open access environment. Since the participants and their required MW quantities are unpredictable in real-time, we have determined by using random numbers theory. It means, the algorithm will decide the source bus and sink bus as well as their contracted power. For each simulation, we can have either bilateral or multilateral contracts and hence numerous case studies can generate. Here we have given some limited transactions.

5.1 With TCPST

5.1.1. Single Source – Single Sink Simulation Results with TCPST

The base case transmission loss before transaction is 18.0524 MW. It has been increased during tractions and the TCPST controls in line 12–16 are minimized that increased loss at every transaction. Similarly, the voltage deviation index (VDI) is high without TCSC and it is also decreased with TCPST. Finally, the transmission losses as well as VDI are optimized at every bilateral transaction as given in Table 3.

The performance characteristics of PSO-GSA for first transaction are illustrated for voltage profile as well as transmission loss in each transmission line are illustrated in Fig. 1 and Fig. 2 respectively.

Table 3. TCPST impact on losses and VDI for single source – single sinks transactions

Source	Sink	Contracted Power (MW)	Transmission losses (MW)			VDI	
			Before transaction	After transaction	With TCPST	Without TCPST	With TCPST
13	16	1.114	18.0524	19.9794	16.2055	0.012046	0.0072891
11	16	4.458	18.0524	19.0341	16.8536	0.011178	0.0072886
2	8	1.62	18.0524	19.0729	16.9496	0.0087398	0.0073145
5	20	4.956	18.0524	20.8488	16.9301	0.012125	0.0073282
8	2	1.802	18.0524	17.8908	16.9269	0.013845	0.0072623

5.1.2. Single Source – Multiple Sinks Simulation Results with TCPST

In section 5.1, we have executed only with one source bus and one sink bus. In this section, one source bus and two sink buses are considered for each transaction. The combined increased load at two sink buses is supplied by one source bus. The multilateral contracts and system performance with TCPST are given in Table 4 and Table 5 respectively.

For multiple sources – single sink transactions and corresponding TCPST impact on system performance are given in Table 6 and Table 7 respectively. Similarly, for multiple sources – multiple sinks and corresponding TCPST impact on system performance are given in Table 8 and Table 9 respectively.

Table 4. Multilateral transactions for single source – multiple sinks simulations

Source	Sinks			Contracted Power (MW)			
				At sink 1	At sink 2	At sink 3	Total
13	24	24	18	4.7680	1.4440	1.6540	7.8660
2	14	4	8	1.1340	2.1910	3.5030	6.8280
1	16	17	15	1.9770	2.2970	3.0380	7.3120
1	16	3	17	2.5030	4.5580	3.0480	10.1090
5	15	23	30	4.4460	3.5800	3.4770	11.5030

Table 5. TCPST impact on losses and voltage VDI for single source – multiple sinks simulations

Transmission losses (MW)			VDI	
Before Transaction	After transaction	With TCPST	Without TCPST	With TCPST
18.0524	18.9428	17.4178	0.010698	0.0073391
18.0524	21.6983	16.9484	0.013126	0.0073258
18.0524	19.0186	17.3977	0.021109	0.0073208
18.0524	18.7147	16.5567	0.029984	0.0072327
18.0524	20.7028	16.7609	0.014798	0.0073658

5.1.3. Multiple Sources – Single Sink Simulation Results with TCPST

Table 6. Multilateral transactions for multiple sources – single sink simulations

Sources			Sink	Contracted Power (MW)			
				At source 1	At source 2	At source 3	Total
8	11	2	24	1.0630	3.7420	2.7540	7.5590
11	11	1	16	2.9230	2.0520	4.8940	9.8690
2	5	11	12	3.6840	4.7270	2.5100	10.9210
8	13	1	8	4.8090	1.9930	2.7300	9.5320
1	5	8	26	4.3800	1.4250	3.0130	8.8180

Table 7. TCPST impact on losses and voltage VDI for multiple sources – single sink simulations

Transmission losses (MW)			VDI	
Before Transaction	After transaction	With TCPST	Without TCPST	With TCPST
18.0524	17.5893	16.4034	0.012418	0.0073336
18.0524	18.8399	17.144	0.016708	0.0073349
18.0524	19.9077	17.5496	0.018664	0.0073082
18.0524	18.2232	17.5021	0.010239	0.0073271
18.0524	18.6513	16.8284	0.014459	0.0072731

5.1.4. Multiple Sources – Multiple Sinks Simulation Results with TCPST

Table 8. Multilateral transactions for multiple sources – multiple sinks simulations

Sources		Sinks		Contracted Power (MW)				
				At source 1	At source 2	At sink 1	At sink 2	Total
11	2	16	12	2.2000	2.6650	2.2000	2.6650	4.8650
2	5	10	16	3.6230	1.8660	3.6230	1.8660	5.4890
2	8	2	3	4.1970	3.5490	4.1970	3.5490	7.7460
11	11	19	23	3.6800	2.3560	3.6800	2.3560	6.0360
11	13	21	17	1.9810	1.5550	1.9810	1.5550	3.5360

Table 9. TCPST impact on losses and voltage VDI for multiple sources – multiple sink simulations

Transmission losses (MW)			VDI	
Before Transaction	After transaction	With TCPST	Without TCPST	With TCPST
18.0524	20.4394	17.3873	0.022854	0.0072904
18.0524	18.3073	17.4353	0.0079498	0.0073024
18.0524	19.9373	17.6502	0.012314	0.0073631
18.0524	20.7416	17.5492	0.020786	0.007282
18.0524	21.4521	17.5443	0.011449	0.0072908

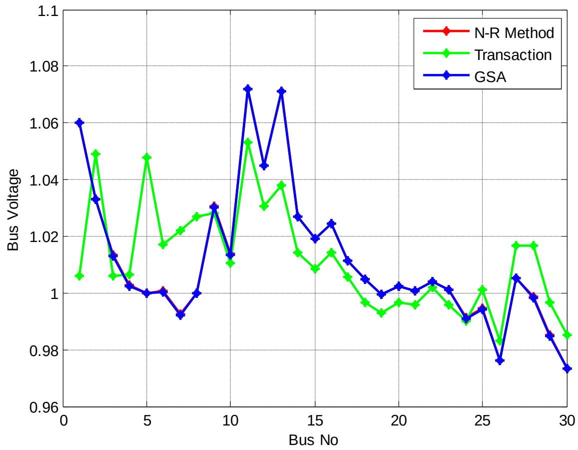

Fig. 1. Bus System voltage profile with TCPST

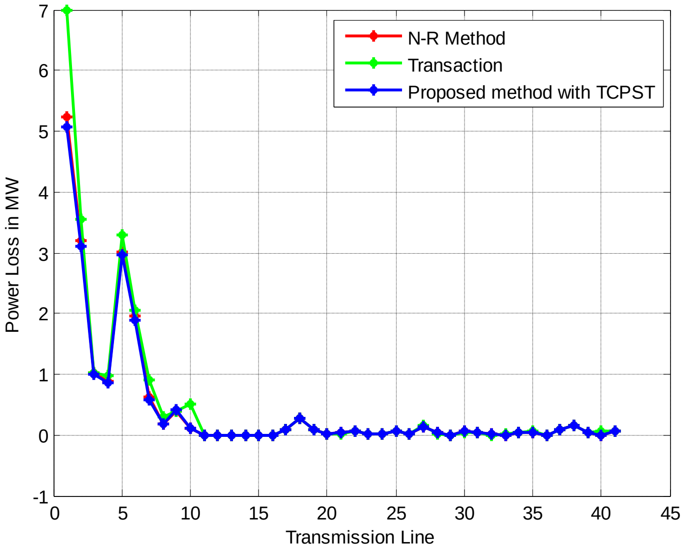

Fig. 2. Loss in each transmission line with TCPST

5.2. With IPFC

5.2.1. Multiple Sources – Multiple Sinks Simulation Results with IPFC

The base case transmission loss before transaction is 18.0524 MW. It has been increased during tractions and the IPFC controls in line 12–15-16 are minimized that increased loss at every transaction. Similarly, the voltage deviation index (VDI) is high without IPFC and it is also decreased with IPFC. Finally, the transmission losses as well as VDI are optimized at every multilateral transaction as given in Table 10 and Table 11 respectively. The voltage profile as well as transmission loss in each transmission line are illustrated in Fig. 3 and Fig. 4 respectively.

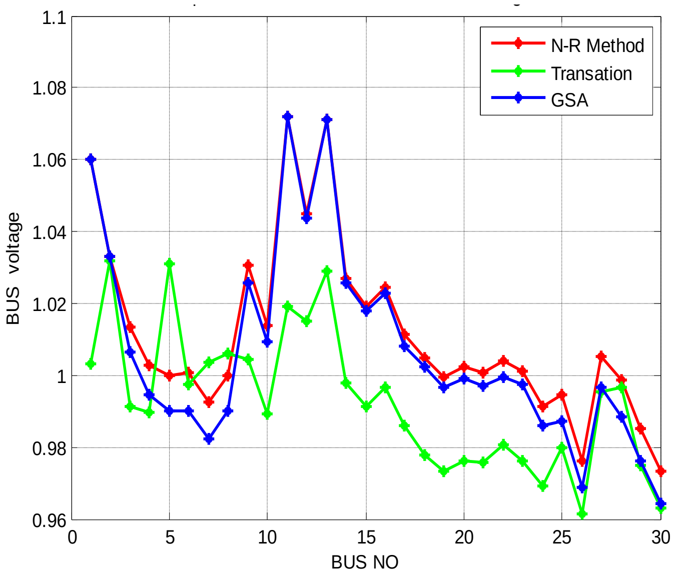

Fig. 4. Bus voltage profile with IPFC

Table 10. IPFC impact on losses and VDI for single source – single sinks transactions

Source	Sink	Contracted Power (MW)	Transmission losses (MW)			VDI	
			Before transaction	After transaction	With IPFC	Without IPFC	With IPFC
5	14	4.917	18.0524	19.2266	16.907	0.1161	0.012462
11	30	3.316	18.0524	18.8323	18.2391	0.14014	0.02457
5	21	1.745	18.0524	17.9059	16.8218	0.11413	0.0080656
1	19	4.059	18.0524	18.679	16.8295	0.10518	0.023328
1	4	4.717	18.0524	20.5078	8.722	0.10895	0.028008

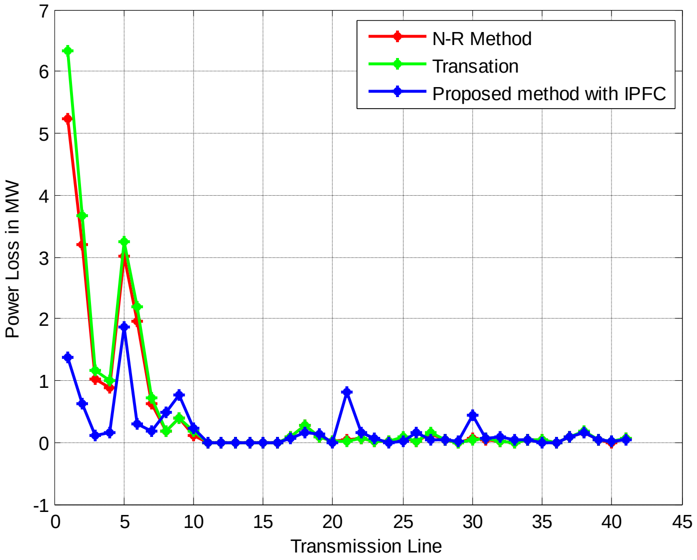

Fig. 5. Loss in each transmission line with IPFC

VI. Conclusion

In open access transmission system, the transactions can take place at any time among various market participants. Some transactions can cause to decrease total transmission losses due to counter flows and some are cause to increase due to dominant flows. Irrespective of transactions and their volumes, the major responsibility of power system engineers is to decrease net transmission losses as well as to maintain good voltage profile for the better performance of system. In this paper, the impact of TCPST and IPFC on system performance is analyzed for both bilateral and multilateral transactions. It has been observed that the transmission losses are decreased and voltage profile is increased significantly with FACTS controllers in the network. The adopted hybrid algorithm GSA-PSO is proved its ability to solve complex optimization problem with multiple objectives.

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