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Optimal Coordination of Directional Overcurrent Relays Using Sine Cosine Algorithm

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Abstract

Integration of the distributed generator (DG)s into the power system and distribution network has increased the complexity of protection coordination. The Optimal coordination of directional overcurrent relay (DOCR)s used for the protection of such networks is highly constrained and nonlinear. A nonlinear optimization technique called Sine Cosine Algorithm (SCA) is used in this paper to solve the optimal coordination problem of the DOCRs. The SCA is a recently proposed algorithm for solving highly nonlinear constrained optimization problems. The method uses the cyclic nature of the sinusoids to reposition a solution around another best solution. This is used to exploit the region defined by the constraints to look for a global optimum value. This work implements the SCA to optimize the coordination problems for the IEEE 3-Bus, 15-Bus and 30-Bus test systems. The result shows the robustness of the algorithm to reduce the total operating times of primary relays while simultaneously maintaining the coordination time intervals (CTI) between the primary and backup relay pairs.

Keywords

Directional Over-current Relay Coordination, Coordination Time Interval, Distributed Generator, Sine Cosine Algorithm

1. Introduction

Directional Overcurrent Relay (DOCR)s along with isolators and circuit breakers are used in the protection of the power system network. Due to high penetration of renewable energies and the distributed generators, the structure of the power system as well as distribution system network has become meshed. The integration of the distributed generation has various technical, environmental and economic benefits. The magnitude of the short circuit current depends upon the nature and the penetration of the DGs. In order to protect the system, fast and reliable operation of the DOCR is required. The optimal coordination of the relays plays a vital role in protecting the system. The relays should operate such that the fault is isolated without damaging the network. The main function of the DOCR is to detect the fault in its protective zone without any intentional delay. This type of protection is known as the primary protection. Sometime the primary protection may fail to protect due to various reason such as disfunction of primary relays, isolator not working and so on. In this case, after certain interval of time the backup protection should isolate the fault. The backup protection is an additional security measure that is provided to a section or protective zone which activates only if the primary protection fails to operate after a certain intentional delay. The operation time of the individual relay depends upon the two settings available. These are the Time Multiplier Settings (TMS) and the Plug Settings (PS). There have been different approaches to adjust the TMS and the PS to obtain the minimum total operation time. Most of these approaches fix the PS of the relay to predetermined constant value and only optimizes the TMS. This is done due to the reason that the operation time of the relay is nonlinear function of its PS while a linear function of its TMS. This approach uses linear programming techniques such as Simplex, Dual-Simplex and Two-Phase methods to optimize the values of the TMS only.

The nonlinear programming techniques such as Genetic Algorithm, Improved Grey Wolf Optimizer, Hybrid Whale Optimization, Fuzzy logics, Mixed Integer Programming, Ant-lion Optimization and so on can be used to solve the DOCR coordination problem. One of the such techniques is Sine Cosine Algorithm (SCA), which is used in this work and was first introduced in [1]. These nonlinear optimization techniques can be used to optimize both the PS and the TMS of a relay to ensure the minimum total operating time of the primary relays. It should be noted that the derivative based optimization techniques could be trapped in a local minima and fails to achieve the global minimum. The rate of convergence of such algorithms depends on the system size being considered and are slow with the increase in system size.

2. Approach

2.1 Formulation of the objective function

Relay coordination problem can be formulated as a linear or nonlinear function. In case of linear approach PS is kept constant while the TMS is optimized whereas in case of nonlinear function both the PS and TMS are simultaneously optimized for the minimum total operational time of the primary relays. The relay characteristics can be mathematically expressed as [2].

$$T_{ik} = \frac{TMS_i \times \beta}{\left(\frac{I_{Rik}}{PS_i}\right)^{\alpha} - 1} \tag{1}$$

where,
T_{i_k} is operational time of the relay i for the fault at location k;

TMS_i is the Time Multiplier Setting of the relay i;
PS_i is the Plug Setting of the relay i;
I_{Rik} is fault current seen by relay i for the fault at location k;
α and β are constants which vary with the characteristics of the relay.

For Inverse Definite Minimum Time (IDMT) relay α and β have values 0.02 and 0.14 respectively [3]. The objective of the relay coordination problem is to determine the values of TMS and PS for each relay such that the total operation time of the primary relays will be minimum. Therefore, the objective function will be

Minimize

$$Z = \sum_{i}^{n} \sum_{k=1}^{l} w_{ik} T_{ik} \tag{2}$$

where,
T_{ik} is the operation time of relay i for the fault at location k.
w_{ik} is the product of probability of occurrence of the fault and relative importance of the line/bus on which the fault occurs. In this paper, w_{ik} is taken to be 1.

The optimization problem has the following constraints

- Plug Setting Constraints

  The PS settings should be within the available range. i.e.,

  $$PS_{i,min} \le PS_i \le PS_{i,max} \tag{3}$$

  The minimum and maximum PS setting available for all the relays are taken to be 0.5 and 2.5 respectively.

- Time Multiplier Settings Constraints

  The TMS settings should be within the available range. i.e.,

  $$TMS_{i,min} \le TMS_i \le TMS_{i,max} \tag{4}$$

  The minimum and maximum TMS setting available for all the relays are taken to be 0.1 and 5 respectively.

- Operating time Constraints

  The limits on the relay operating time can be expressed as

  $$T_{ik,min} \le T_{ik} \le T_{ik,max} \tag{5}$$

  The minimum and maximum operating time of all the relays are taken to be 0.1 seconds and 2 seconds respectively.

- Coordination Constraints

  For a a fault at location k, the primary relay i should operate before backup relay j. The time delay after which the backup relay works if the primary relay fails to isolate the fault is known as Coordination Time Interval (CTI) and this constraint can be expressed as

  $$T_{jk} - T_{ik} \ge CTI \tag{6}$$

  For all primary and backup pairs i and j, the CTI used in this paper is 0.3 seconds.

2.2 Sine Cosine Algorithm to solve nonlinear optimization problem

The SCA is a unique optimization technique which is inspired from the basic sinusoidal and co-sinusoidal function and was first introduced in [1].

The SCA develops a set of random initial population which oscillates inward or outwards of the current best solution to achieve the next best solution by exploring the region defined by the constraints. The equation to update the position of the population can be expressed as [1]

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin(r_2) \times \left| r_3 P_i^t - X_i^t \right| & \text{if} \quad r_4 < 0.5 \\ X_i^t + r_1 \times \cos(r_2) \times \left| r_3 P_i^t - X_i^t \right| & \text{if} \quad r_4 \ge 0.5 \end{cases} \tag{7}$$

where, X_i^t is the position of the current solution in i^{th} dimension and t^{th} iteration X_i^{t+1} is the position of the current solution in i^{th} dimension and $(t+1)^{th}$ iteration P_i^t is the best position of the current solution in i^{th} dimension and upto t^{th} iteration $r_1 = a - t(a/T)$, $r_2 \in [0, 2\pi]$, $r_3 \in [0, 2]$, $r_4 \in [0, 1]$

$a = 2$, t is the current iteration and T is the maximum number of iterations.

r_2, r_3 and r_4 are the random numbers.

The SCA stores the best solution in a variable P_i^t as a destination point and all the other solution moves toward that destination using equation 7.

The SCA can be described best by the flowchart shown in Figure 1.

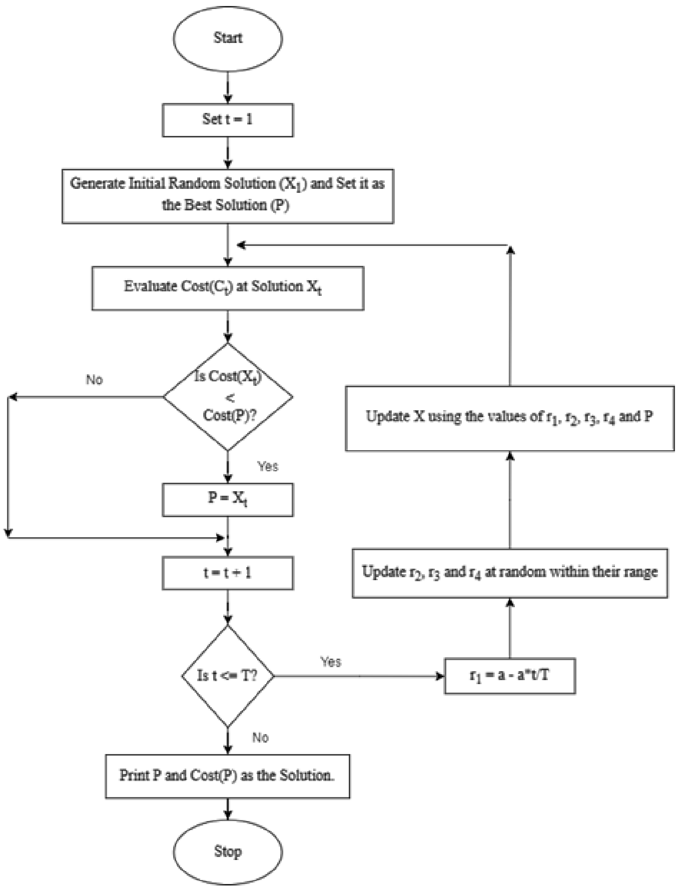

Figure 1: SCA for nonlinear optimization

3. Result and Discussion

The proposed algorithm was tested on three different test systems: 3-bus, 15-bus and 30-bus system. The IDMT relays were chosen with $\alpha = 0.02$ and $\beta = 0.14$. The CTI constraints for all the relays were assumed to be 0.3 seconds. In all three cases the population size was taken to be 1000 and the SCA program was run for 1000 iterations. The obtained results is then compared with various other optimization techniques shown in Table 4.

3.1 Three-bus test system

A three-bus test system having three buses, three lines, three generators and six relays as shown in Figure 2. was considered. The rating of each of the components is given in [4]. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results as shown in Table 1.

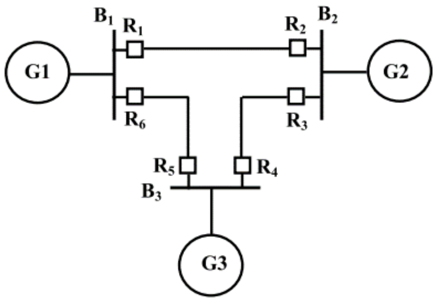

Figure 2: SLD of three-bus test system

Table 1: Results for three-bus test system

Relay	Primary Operation			Backup Operation			CTI (seconds)
	TMS	PS	Top (seconds)	TMS	PS	Top (seconds)	
1	0.13089	0.52292	0.22107	0.33287	0.6639	0.7671	0.54603
2	0.10672	1.5493	0.22144	0.27734	0.6165	0.69013	0.46869
3	0.13886	0.66325	0.22092	0.24633	1.2068	0.68818	0.46727
4	0.10263	1.3664	0.22101	0.28583	0.59299	0.65156	0.43055
5	0.1	2.0032	0.22742	0.17998	1.7752	0.71555	0.48813
6	0.1	1.1086	0.22328	0.2454	0.88076	0.77131	0.54803
Total Operation Time		1.33514 seconds					

Table 1 shows the simulation results for three-bus test system. The proposed algorithm shows that it will take 1.33514 seconds to operate all the primary relays. Also, it is found that all of the constraints are met. Furthermore Figure 3 shows the convergence characteristics for the three-bus test system. It is clearly seen that the program was able to converge at around 300 iterations.

3.2 Fifteen-bus test system

A fifteen-bus test system connected to an external grid at bus eight and having six generators, twenty-one lines and forty-two relays as shown in Figure 4 was considered. The rating of each of the components is given in [5]. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results as shown in Table 2.

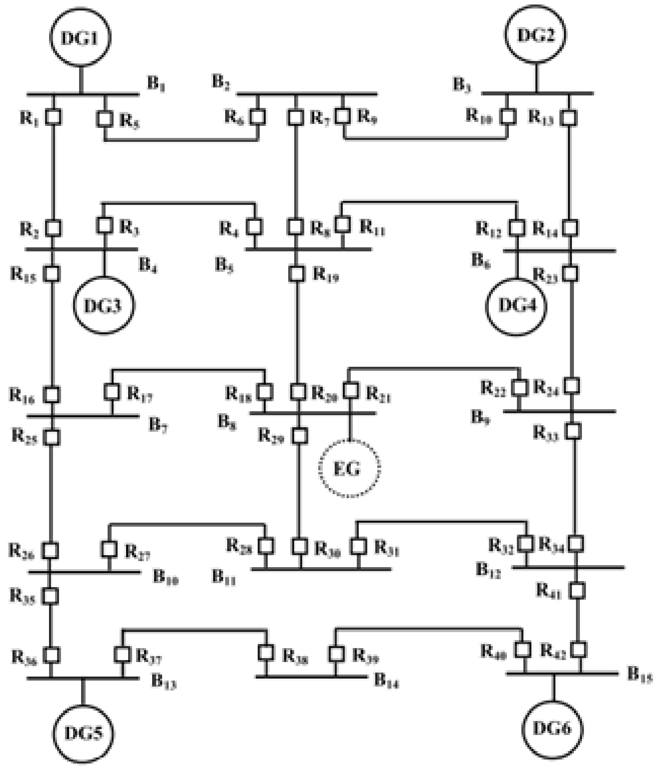

Figure 3: SLD of fifteen-bus test system

Table 2: Results for fifteen-bus test system

Relay	Primary Operation			Backup Operation			CTI (seconds)
	TMS	PS	Top (seconds)	TMS	PS	Top (seconds)	
1	0.10407	1.1962	0.24056	0.25405	1.4514	1.3492	1.1086409
2	0.19147	0.68061	0.38835	0.1	2.4777	1.58877	1.2004251
3	0.17549	0.55252	0.31048	0.50358	0.5909	1.26474	0.9542591
4	0.16313	1.3247	0.42397	0.45696	0.51096	1.25364	0.82967
5	0.174	0.51164	0.31691	0.72766	0.62029	1.87559	1.5586771
6	0.10154	0.98778	0.22179	0.69369	0.74057	1.79809	1.5762947
7	0.10207	2.0015	0.29802	0.31542	2.3633	1.59492	1.2969065
8	0.16818	0.50335	0.31002	0.24506	2.4527	1.75706	1.4470452
9	0.15485	0.53893	0.2732	0.44964	1.4071	1.72916	1.4559543
10	0.18406	0.79938	0.37436	0.31917	1.5226	1.45985	1.0854863
11	0.12724	0.657	0.25976	0.26254	2.4685	1.99639	1.7366266
12	0.1	0.52566	0.19284	0.28763	2.0831	1.85501	1.6621686
13	0.10002	1.2048	0.23699	0.30521	0.69027	0.79716	0.5601698
14	0.10883	1.0615	0.25562	0.10321	1.8291	0.72657	0.4709489
15	0.12348	0.53496	0.23139	0.3977	0.93006	1.86836	1.6369712
16	0.13304	0.98164	0.30766	0.30765	1.052	1.19353	0.8858663
17	0.14401	0.58925	0.26375	0.64879	0.68538	1.85441	1.5906624
18	0.1143	0.92426	0.23097	0.15782	1.7501	1.27747	1.046504
19	0.20434	0.50415	0.35244	0.23601	2.351	1.26037	0.9079274
20	0.13539	0.59669	0.24731	0.36862	0.5713	1.10062	0.8533029
21	0.10022	2.0736	0.2696	0.1869	1.6816	1.43754	1.1679312
22	0.13124	0.50012	0.22731	0.48278	1.0048	1.59292	1.3656078
23	0.10112	0.52394	0.18616	0.3825	0.77588	1.5867	1.4005414
24	0.11523	0.56638	0.22124	0.23595	0.57622	0.67531	0.454064
25	0.14789	1.7271	0.42071	0.29627	1.4842	1.25701	0.8363011
26	0.1719	2.0523	0.52662	0.3533	2.2232	1.99997	1.4733491
27	0.10173	1.9193	0.32157	0.3592	0.99772	1.13876	0.8171926
28	0.18267	0.61511	0.34935	0.35858	2.2573	1.66907	1.3197268
29	0.10129	0.60821	0.18164	0.69665	0.52819	1.9997	1.8180659
30	0.10192	2.5	0.32293	0.49312	1.4568	1.92179	1.598865
31	0.1428	0.52758	0.25225	0.40354	0.72054	1.23522	0.982966
32	0.11035	1.724	0.32775	0.32776	1.3724	1.5673	1.2395457
33	0.15125	1.0564	0.35443	0.47166	0.53386	1.10654	0.7521081
34	0.14292	1.2731	0.34462	0.24666	1.026	0.682	0.3373836
35	0.11961	0.53432	0.23186	0.42043	0.54577	1.08916	0.8573046
36	0.13232	1.4455	0.33992	0.29033	1.0182	1.0395	0.6995788
37	0.10353	1.0793	0.23849	0.2385	1.3265	0.85724	0.6187495
38	0.11086	0.51752	0.21264	0.59212	1.4462	1.99939	1.7867551
39	0.10662	1.5705	0.29913	0.72843	0.53311	1.62446	1.3253353
40	0.10374	1.4863	0.27416	0.11849	2.2872	0.60898	0.3348194
41	0.10297	0.53251	0.18086	0.63955	0.91369	1.88395	1.7030877
42	0.10378	0.5	0.18821	0.31585	1.4842	1.62778	1.43956995
Total Operation Time			12.0079 seconds				

Table 2: shows the simulation results for fifteen-bus test system. The proposed algorithm shows that it will take 12.0078624 seconds to operate all the primary relays. Also, it is found that all of the constraints are met. Furthermore Figure 5. shows the convergence characteristics for the fifteen-bus test system. It is clearly seen that the program was able to converge at around 900 iterations.

3.3 Thirty-bus test system

A thirty-bus test system with thirty buses, twenty lines and thirty-nine relays as shown in Figure 6. was considered. The rating of each of the components is given in [6]. The three phase to ground faults were considered to occur at the mid-point of the line. The developed SCA program was then run to obtain the following results as shown in Table 3 which shows the simulation results for thirty-bus test system.

Table 3: Results for thirty-bus test system

Relay	Primary Operation			Backup Operation			CTI (seconds)
	TMS	PS	Top (seconds)	TMS	PS	Top (seconds)	
1	0.24379	1.1722	0.41383	0.2848	1.6304	0.76864	0.35481
2	0.12223	0.50545	0.30155	0.1841	1.9049	0.73415	0.4326
3	0.22559	0.50181	0.34345	0.24956	2.2334	0.8599	0.51645
4	0.23715	1.3746	0.58188	0.38125	1.0184	0.96556	0.38368
5	0.24537	1.4807	0.6077	0.25874	1.99	0.98596	0.37826
6	0.12979	0.65199	0.35402	0.4704	0.52599	1.129	0.77498
7	0.1202	0.50079	0.20018	0.28001	0.53041	0.72575	0.52557
8	0.10347	0.66358	0.18632	0.11191	1.0523	0.48649	0.30017
9	0.12399	0.71131	0.1713	0.23046	1.0322	0.48914	0.31784
10	0.1779	0.50142	0.35481	0.52424	0.67714	1.0964	0.74159
11	0.41835	1.4075	0.81718	0.36326	1.5186	1.1061	0.28892
12	0.28902	0.5015	0.44712	0.41456	1.4533	1.2315	0.78438
13	0.11368	1.1927	0.56858	0.26462	2.2163	1.0152	0.44662
14	0.10838	1.3924	0.2801	0.27019	0.64778	0.7214	0.4413
15	0.11375	0.53959	0.26551	0.11358	1.9722	0.57941	0.3139
16	0.31127	0.55813	0.38234	0.30873	1.8949	1.0024	0.62006
17	0.14957	0.70268	0.39301	0.31427	0.53499	1.0708	0.67779
18	0.2104	0.5016	0.31541	0.27041	1.3394	0.86289	0.54748
19	0.14832	1.5894	0.45573	0.37645	1.4235	1.1024	0.64667
20	0.18264	0.75182	0.30332	0.22236	1.4597	1.197	0.89368
21	0.1341	0.7054	0.24292	0.20102	0.7687	0.91536	0.67244
22	0.18509	1.414	0.45936	0.43356	1.4834	1.2023	0.74294
23	0.2447	0.82127	0.54577	0.4023	0.61604	0.95015	0.40438
24	0.16437	2.2544	0.45404	0.23955	2.0012	1.1345	0.68046
25	0.23221	0.68268	0.75012	0.31475	1.9672	1.1231	0.37298
26	0.1043	0.9787	0.30511	0.37375	0.95432	0.92074	0.61563
27	0.10458	0.5	1.31227	0.26753	1.0013	0.72657	0.5857
28	0.13754	0.82906	0.31348	0.25001	1.6117	1.0961	0.78262
29	0.1027	1.607	0.22525	0.13136	2.0012	0.73388	0.50863
30	0.10966	0.62741	0.38289	0.35608	1.2348	1.0485	0.66561
31	0.1389	0.86591	0.21938	0.16495	2.2239	0.74728	0.5279
32	0.24032	0.51542	0.48594	0.50132	0.50702	1.1145	0.62856
33	0.12653	0.5071	0.33929	0.2831	2.4222	1.0191	0.67981
34	0.16117	1.1425	0.24557	0.17508	1.932	0.59269	0.34712
35	0.10007	0.67991	0.19279	0.161	1.8106	0.67186	0.47907
36	0.15916	1.2631	0.54535	0.24761	1.5632	1.0923	0.54695
37	0.16596	0.81726	0.30793	0.25393	1.7567	1.016	0.70807
38	0.11637	0.93111	0.28046	0.20888	2.2078	0.9922	0.71174
39	0.12123	0.73835	0.24701	0.30054	1.5634	1.0862	0.83919
Total Operation Time			15.59827 seconds				

The proposed algorithm shows that it will take 15.59827 seconds to operate all the primary relays. Also, it is found that all of the constraints are met. Furthermore Figure 7: shows the convergence characteristics for the fifteen-bus test system. It is clearly seen that the program was able to converge at around 900 iterations.

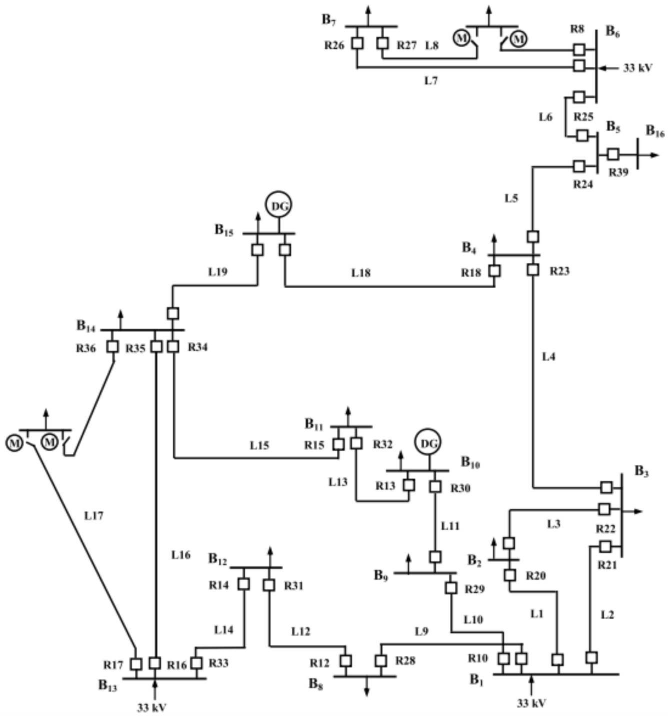

Figure 4: SLD of thirty-bus test system

Table 4: Comparision with various other optimization techniques

SYSTEM	Total Operation Time (s)						
	Proposed (SCA)	SA [5]	IGWO [7]	HWOA [8]	SBB [5]	DE [9]	HS [9]
3 BUS	1.33514	1.599	1.4789	1.5029	-	-	
15 BUS	12.00786	12.227	12.6446	-	15.335	-	-
30 BUS	15.59287	-	-	-	-	17.8122	19.2133

4. Conclusion

In this paper optimal coordination problem was formulated and the SCA program was coded in MATLAB to solve such problems. Then the said program was run to solve the coordination problem. The algorithm was used on three different test bus system viz. three-bus test system, fifteen-bus test system and thirty-bus test system. The optimized values of the TMS and PS settings for individual relays were obtained for the minimum total operation time of the primary relays and were tabulated in section 3. The results obtained were then compared with the results from the various optimization techniques shown in Table 4. The result shows the effectiveness of the proposed algorithm to solve non linear optimization problem which can also be applied to solve the DOCR coordination problem. The results shows that the obtained PS values are continuous rather than discrete i.e., the obtained values are not obtained in steps. The PS values are generally available in discrete steps of 0.5. The SCA could be coupled with mixed integer programming techniques to obtain the PS as a discrete value, and if required TMS also could be obtained as a discrete value.

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