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Optimal Allocation with Network Limitation for Autonomous Space Power System

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A new approach is presented to congestion analysis and optimal load shedding for aerospace power systems. Optimal power flow, an analytic hierarchical process, and the Everett optimization method (Everett, H., *Operations Research*, Vol. 11, 1963, pp. 399–417) are employed for implementing this approach. Several system performance indices are developed to evaluate the degree of system congestion for different operation time stages. These performance indices include a circuit overload index and a system voltage problem index obtained through the optimal power flow calculation. The congested system is alleviated by the available control such as load shedding. Therefore, the mathematical model of load shedding, in which the objective is a payoff function, is devised. The solution method of the model is the Everett method, generalized Lagrange multipliers. Detailed results are given in the paper.

Nomenclature

C^K	=	resource functions ($k = 1, 2, \ldots, k$)
H	=	payoff function
$H(x)$	=	payoff (or utility) that accrues from employing the strategy $x \in S$
K_{ij}	=	weight factor of line ij, which may be provided by operators
MPI	=	unified performance index
N	=	total number of nodes in the system
$ND(k)$	=	total number of load sites in load center k
NT	=	total number of transmission lines in the system
P_D	=	total amount of system load available at the ith time stage
P_{Dij}	=	load demand of the jth load site of the ith time stage
P_{ij}	=	power flow on transmission line ij
$P_{ij\,\max}$	=	power limit of transmission line ij
P_{iK}	=	total amount of load center k available at the ith time stage
P_{SK}	=	transmission power on the line connecting the load center k
$P_{SK\,\mathrm{ATC}}$	=	available transfer capacity (ATC) of the line connecting the load center k
PI_M	=	relative importance index of different operation time stages, which may be obtained according to the operator's experiences
PI_P, PI_V	=	megawatt- (MW) and megavolt argon- (MVAr-) type performance indices, respectively
S	=	set that is interpreted as the set of possible strategies or actions
SPI_{PTC}	=	effect of transfer capacity of line ij to MW-type congestion degree
SPI_{VTC}	=	effect of transfer capacity of line ij to MVAr type congestion degree
V_e	=	rated voltage in the system
V_i	=	node voltage on bus i
$V_{i\,\max}$, $V_{i\,\min}$	=	node voltage upper and lower limits on bus i
v_{ij}	=	independent load values in a specific load bus j at the ith time stage
W_P, W_V, W_M	=	weighting coefficients of congestion indices PI_P, PI_V, and PI_M, respectively
x_{ij}	=	decision variable (equal to 0 or 1) on load bus j at the ith time stage
α_{ij}	=	absolute load priority to indicate the importance of the jth load site of the ith time stage.

Introduction

THE aerospace electrical power system of the space station is similar to terrestrial power systems. Operation of terrestrial power utilities is based on command and control strategies for each of four operation states: normal, preventive, emergency, and restorative. Aerospace electrical power systems will also incorporate these strategies.[1] Oversight decisions must be made to choose those strategies that will keep the power system operating within tolerance and as productive as possible under all circumstances.[2] In the new competitive power environment, buy/sell decision support systems are to find economical ways to serve critical loads with limited sources under various uncertainties. Decision making is significantly affected by limited energy sources, generation cost, and network available transfer capacity. Generally, the congested system can be reduced through some control strategy such as a generation rescheduling scheme, as well as obtaining power support from a neighboring utility. NASA's Space Station Freedom, however, does not have the advantage of purchasing power from a neighboring utility. In the case of Space Station Freedom, the control strategy is to maximize solar energy conversion and to control energy utilization by adding and deleting loads from the system. This, in turn, requires that the load demand be as deterministic as possible so that each watt can be allocated.[1]

The research work in this area includes 1) time-dependent system congestion and capability analysis, 2) time-dependent optimal allocation of power sources under different load demands, and 3) a value-driven load-shedding scheme to alleviate system congestion.

This paper studies aerospace power system automation using the optimal power flow (OPF) and the Everett optimization method,[3]

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generalized Lagrange multipliers. Several system performance indices are developed to evaluate the degree of system congestion for different operation time stages. These performance indices include a circuit overload index and a system voltage problem index. The former is called the megawatt- (MW-) type congestion index, and the latter is called the megavolt argon- (MVAr-) type congestion index. Both MW and MVAr congestion indices are computed based on the OPF calculation.[4] Because the congestion of the system is time dependent, this paper presents an analytic hierarchical process (AHP) method[5,6] to solve the time-dependent congestion ranking in the new environment, coordinating the MW and MVAr congestion ranking as well as considering the experience of operators or engineers.

The congested system is alleviated by the available control such as load shedding. To minimize the congestion, the mathematical model of load shedding, in which the objective is a payoff function, is devised. The Everett method,[3] generalized Lagrange multipliers, is employed to solve the problem. The proposed model and method are examined on a NASA benchmark system and an Institute of Electrical and Electronics Engineers (IEEE) 30-bus system designed for testing the algorithm. The scheme can be tested for other large systems. The calculation results show that the proposed model and its algorithm are feasible and effective.

Performance Index for Congestion Analysis

It is necessary to evaluate or to calculate the degree of congestion based on analysis of a power system under different system operating conditions. In this regard, the suitable performance indices can be determined. The congestion degree of a power system, in fact, reflects the security operation level of the system under the given operation conditions. Therefore, the circuit flow overload index and voltage problem index are used for system congestion analysis in this paper. The former is designated as an MW-type congestion index and the latter as an MVAr-type congestion index because voltage is coupled with volt argon dispatch. Let P_{ij} be the power flow on transmission line ij and V_i the node voltage on bus i; the definitions of these two performance indices are given as follows:

$$PI_P = \sum_{ij=1}^{NT} K_{ij}\left(\frac{P_{ij}}{P_{ij\,\max}}\right)^2 \tag{1}$$

$$PI_V = \sum_{i=1}^{N}\left[\frac{2(V_i - V_e)}{V_{i\,\max} - V_{i\,\min}}\right]^2 \tag{2}$$

Both the line real power P_{ij} and the node voltage V_i in Eqs. (1) and (2) can be obtained using quadratic interior point optimization technique for solving OPF under different contingencies.[4]

Hierarchy Model of Congestion Ranking

There are different operation stages in one operational period of the given power system under study. Let PI_M be the relative importance index comparing the value of load level at a given time duration T. This index shows the relative importance of the time stage based on the operator's experiences. Note that the multi-indices PI_P, PI_V, and PI_M reflect the congestion degree in the system under the different operation conditions. However, the congestion results from these multi-indices are not necessarily the same due to their different measurements. The problem is how to find a unified MPI process for treating or ranking these results; that is,

$$\text{MPI} = W_P \times PI_P + W_V \times PI_V + W_M \times PI_M$$

$$W_P + W_V + W_M = 1 \tag{3}$$

There are two difficulties in solving Eq. (3). One difficulty is that it is impractical to give exact data for index PI_M, and the other is how to obtain the weighting coefficients W_P, W_V, and W_M in the calculation of MPI. By the using of an AHP, this difficulty can be accommodated. AHP can help in quantifying the decision maker's thinking, and it can be used to calculate a unified congestion ranking

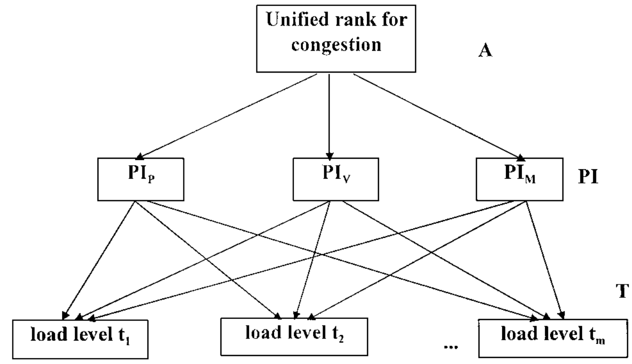

Fig. 1 Hierarchy model of congestion rank.

for MW and MVAr subproblems in power systems, according to some judgement matrix. The judgment matrix can be formed based on the experience and needs of the engineer. Satty[5] and Zhu[6] provide adequate background on AHP and its power system application, respectively.

To obtain a unified congestion ranking list, a hierarchy model of congestion ranking should be set up, as in Fig. 1, according to the principle of AHP.[5,6] The hierarchy model of congestion rank consists of three sections. The first section contains the unified rank of congestion degree for different time stages. The second one contains the performance indices, in which the PI_M (redefined earlier) is to reflect the relative importance of different time stages in a new environment. The last one deals with the congestion degree at different time stages.

The PI_P and PI_V were obtained by using eigenvectors through normalization. The PI_M are computed from the judgment matrix.

Control Actions for Alleviating Congestion

It is obvious that the congestion degree of a system is time dependent. In particular, in a competitive resource allocation environment, buy/sell decision support systems are needed to find economical ways to serve critical loads with limited sources under different uncertainties. For example, it is clear that the limited energy sources and their cost and the network transfer limitations significantly affect decision making. To cope with the congestion and transfer requirement, space power system operation requests for costing of different sources for various time stages. Therefore, the offline approach and/or design for alleviating network congestion and specifying load optimal allocation is provided in the paper.

A. Increase Transfer Capacity of Transmission Lines

A possible measure to alleviate the congestion of the system is to increase the available transfer capacity of the transmission line or to allow a temporary overload operation of some transmission lines. An index to analyze the effect of transfer capacity of lines due to congestion is defined as follows:

$$\text{SPI}_{P\text{TC}} = -\frac{\mathrm{d}PI_P}{\mathrm{d}P_{ij\,\max}}, \qquad ij = 1, \ldots, NT \tag{4}$$

$$\text{SPI}_{V\text{TC}} = -\frac{\mathrm{d}PI_V}{\mathrm{d}P_{ij\,\max}}, \qquad ij = 1, \ldots, NT \tag{5}$$

The minus symbol in Eqs. (4) and (5) means that the congestion degree of the system will be alleviated when the transfer capacity of a line increases, and it will be aggravated when the transfer capacity of a line is decreased. Accordingly, the values of $\text{SPI}_{P\text{TC}}$ and $\text{SPI}_{V\text{TC}}$ determine the transmission lines whose transfer capacity significantly affects system congestion. These sensitivities are also used to analyze the alleviation of line overload.

B. Load Shedding Scheme by Everett Method[3]

If the congestion of the system is very serious at some of the time stages, it is impractical to alleviate the congestion by increasing the transfer capacity of the line. Therefore, a value-driven, load-shedding approach is proposed for this purpose. The mathematical model of load shedding is expressed as follows.

1. Objective Function: Benefit (or Payoff) Function

The objective function is

$$H_i = \sum_{j=1}^{ND(K)} v_{ij}\alpha_{ij}x_{ij} \tag{6}$$

In Eq. (6), decision variable $x_{ij} = 1$ if load demand P_{ij} is satisfied; otherwise $x_{ij} = 0$ if the load demand is not satisfied, that is, load shed appeared on the jth load site at the ith time stage. There are several values of loads in a power system, such as critical load, important load, unimportant load, etc., and α_{ij} can reflect the relative importance of different kinds of loads. The more important the load site is, for example, first important load, the larger the value of α_{ij} of the load site. Each load is assigned a value given by v_{ij}.

2. Constraints of Load Curtailment

The constraints on load curtailment are reflected as the system congestion cases. These constraints include the limited capacity in each load center and the loads representing the entire system, as well as the available transfer capacity (ATC) of the key line (e.g., tie-line connecting different load center or source), which can be expressed as follows:

$$\sum_{j\in K} P_{Dij}x_{ij} \le P_{iK} \tag{7}$$

$$\sum_{j=1}^{ND} P_{Dij}x_{ij} \le P_D \tag{8}$$

$$\sum_{j\in K} P_{Dij}x_{ij} = P_{SK} \le P_{SK\,\mathrm{ATC}} \tag{9}$$

Equations (7–9) are constraints on load center, power balance, and tie-line, respectively.

The load-shedding problem (6–9) can be solved by Everett optimization techniques.[3] The problem of load shedding can be represented as follows:

$$\max_{\substack{\text{all choices of } \{xi\} \\ xi\ \in\ s}} \sum_{i=1}^{m} H_i(x_i) \tag{10}$$

subject to

$$\sum_{i=1}^{m} C_i^k(x_i) \le c^k \qquad \text{for all} \qquad k \tag{11}$$

where x_i is a zero–one integer variable.

This model is a zero–one integer optimization problem. It is possible to solve problems (10) and (11) using the integer-based optimization techniques. A small scheduling program was developed for a 10-period optimization using a simplistic zero–one integer programming code.[7] This research was further extended with battery charging adequately modeled and using the zero–one optimization method.[8]. However, the scheduling phenomenon was still devoid of many real-life complexities. Ringer and Quinn[9] also developed a scheduler for the space station testbed using the expert system method rather than integer optimization techniques. The shortcoming of this approach is that it does not ensure optimality.

Everett[3] showed that the Lagrange multiplier can be used to solve the maximization problem with many variables without any restrictions on continuity or differentiability of the function being maximized. The aim of the generalized Lagrange multiplier is maximization rather than the location of stationary points as with traditional Lagrange multipliers. This technique is used in this paper. The main theorem of generalized Lagrange multipliers is as follows.

Theorem 1 (Ref. 3). If 1) $\lambda^K (k = 1, 2, \ldots, n)$ are nonnegative real numbers, 2) $x^* \in S$ maximizes the function

$$H(x) - \sum_{K=1}^{n} \lambda^k C^k(x) \qquad \text{over all} \qquad x \in S \tag{12}$$

then 3) X^* maximizes *H(x)* over all of those $x \in S$ such that $C^k \le C^k(x^*)$ for all k.

Proof. By assumptions 1 and 2 of Theorem 1, $\lambda^K (k = 1, 2, \ldots, n)$ are nonnegative real numbers, and $x^* \in S$ maximizes

$$H(x) - \sum_{K=1}^{n} \lambda^k C^k(x)$$

over all $x \in S$. This means that for all $x \in S$,

$$H(x^*) - \sum_{K=1}^{n} \lambda^k C^k(x^*) \ge H(x) - \sum_{K=1}^{n} \lambda^k C^k(x) \tag{13}$$

and, hence, that

$$H(x^*) \ge H(x) + \sum_{K=1}^{n} \lambda^k [C^k(x^*) - C^k(x)] \tag{14}$$

for all $x \in S$. However, if the latter inequality is true for all $x \in S$, it is necessarily true for any subset of S and, hence, true on that subset S^* of S for which the resources never exceed the resources $C^K(x^*)$; that is, $C^K(x) \le C^K(x^*)$, $x \in S^*$ for all k. Thus, on the subset S^* the term

$$\sum_{K=1}^{n} \lambda^k [C^k(x^*) - C^k(x)] \tag{15}$$

is nonnegative by definition of the subset and the nonnegativity of λ^K. Consequently, the inequality reduces to

$$H(x^*) \ge H(x) \tag{16}$$

for all $x \in S^*$, and the theorem is proved.

In accordance with Theorem 1, for any choice of nonnegative $\lambda^K (k = 1, 2, \ldots, n)$, if an unconstrained maximum of the new Lagrangian function [Eq. (12)] can be found (where x^*, for example, is a strategy that produces the maximization), then this solution is a solution to that constrained maximization problem whose constraints are, in fact, the amount of each resource expended in achieving the unconstrained solution. Therefore, if x^* produces the unconstrained maximum and the required resources $C^K(x^*)$, then x^* itself produces the greatest payoff that can be achieved without using additional resource allocation.

Using the Everett method,[3] the problem of load shedding is changed into an unconstrained maximization. The key to solve this problem is choosing the Lagrange multipliers that correspond to the trial prices in the new competitive power market. In general, different choices of the trial prices λ^K lead to different schemes of load shedding, and operators may adjust them according to resources provided and demands of customers to achieve maximal payoff.

Implementation and Simulation

The integrated scheme of index calculation, AHP-based congestion ranking, and Everett-based,[3] load shedding is shown in Fig. 2.

The proposed approach is examined with a NASA John H. Glenn Research Center at Lewis Field benchmark system and an IEEE 30-bus system. For the IEEE 30-bus system, the congestion analysis is made under a high load level ($\Sigma_k P_{Dk} = 340.08$ MW). The congestion degree of the system is calculated: $PI_P^0 = 8.146$ and $PI_V^0 = 5.62$. To analyze the effect of the transfer capacity of each transmission line on the congestion degree, we compute the congestion indices

Table 1 Congestion analysis of IEEE 30-bus system

Line no.	$P_{ij\,\max}$,[a] per unit MW	PI_P	SPI_{PTC}	Line no.	$P_{ij\,\max}$,[a] per unit MW	PI_P	SPI_{PTC}
1	1.560	7.7691	1.4496	22	0.192	8.1179	0.8781
2	1.560	7.9990	0.5654	23	0.192	8.1408	0.1625
3	0.780	8.0900	0.4308	24	0.384	8.1354	0.1656
4	1.560	8.0193	0.4873	25	0.384	8.1271	0.2953
5	1.560	7.9418	0.7854	26	0.384	8.1388	0.1125
6	0.720	7.7280	3.4833	27	0.384	8.0950	0.7969
7	1.080	7.9257	1.2239	28	0.384	8.1341	0.1859
8	0.840	8.1391	0.0493	29	0.384	8.1451	0.0141
9	1.560	8.0795	0.2558	30	0.192	8.1290	0.5313
10	0.384	8.1411	0.0766	31	0.192	8.1217	0.7594
11	0.780	8.1323	0.1054	32	0.192	8.1447	0.0406
12	0.384	8.1110	0.5469	33	0.192	8.1418	0.1313
13	0.780	8.1343	0.0900	34	0.192	8.1351	0.3406
14	0.780	8.0953	0.3900	35	0.192	8.1170	0.9063
15	0.780	8.1087	0.2869	36	0.780	8.1267	0.1485
16	0.780	8.1324	0.1046	37	0.192	8.1128	1.0375
17	0.384	8.1337	0.1922	38	0.192	8.1023	1.3656
18	0.384	8.0815	1.0078	39	0.192	8.1342	0.3688
19	0.384	8.1360	0.1563	40	0.384	8.1428	0.0500
20	0.192	8.1446	0.0438	41	0.384	8.0944	0.8063
21	0.192	8.1369	0.2844				

[a]Power capacities of lines are increased 20%.

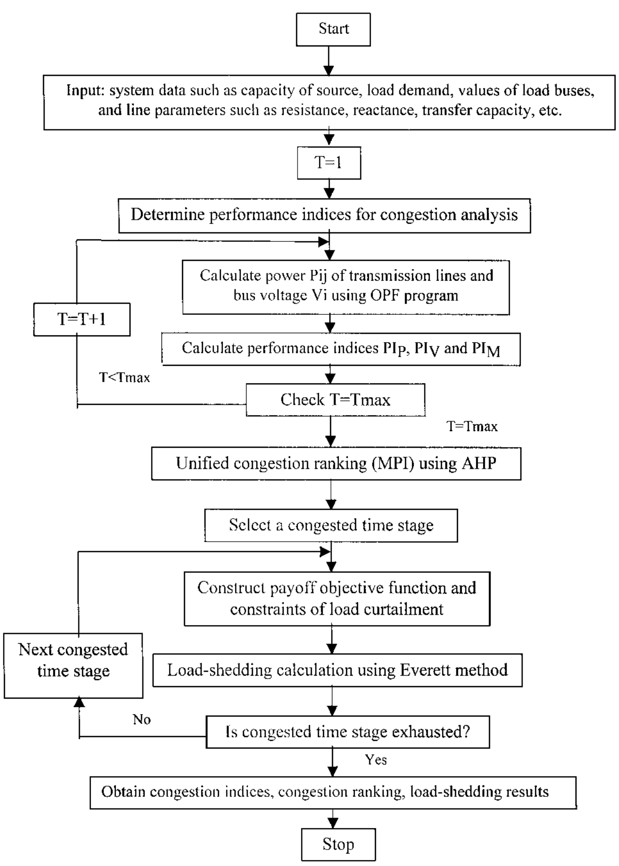

Fig. 2 Flowchart of the integrated congestion ranking and load shedding.

and perform the sensitivity analysis by increasing transfer capacity of the lines by 20%, respectively. The results are listed on Table 1.

It can be observed that the congestion degree of the system has been alleviated by congestion index PI_P when the transfer capacity of the transmission lines is increased by 20%. Thus, for the study, congestion index PI_V has no change. This means that congestion index PI_V is not sensitive to changes in transfer capacity. In addition, the alleviation degree of the system congestion is not the same as the congestion index PI_P caused by the transfer capacity increase of different transmission lines. The results also show that there are six lines whose transfer capacity change will greatly affect the congestion degree of the IEEE 30-bus system, that is, lines 1, 6, 7, 18, 37, and 38 are affected.

Figure 3 is the NASA benchmark power system topology used for the study. It consists of a critical load installed with a remote power-load controller (RPC) acting as load controller for energizing or isolating loads concurrent limits. The source nodes as well as the receiver end nodes of the important transmission line are installed with a remote bus controller (RBC), acting as the bus controller that energizes/isolates bus concurrent limits. In addition, there is a remote tie-line controller (RTC) on each tie-bus that connects different subsystems. The purpose of the bus transfer controller RTC is to energize or isolate critical buses from one of two feeder lines. To coordinate the system operation case, two kinds of hierarchical operation modules in the NASA benchmark system are proposed. One is the lowest module, in which load shedding would be executed. The second is a higher module, in which there exists a pricing scheme to allocate power based on the value of the load. The power generation sources are limited by $0.1 \leq P_{G1} \leq 0.7$ per unit MW and $0.1 \leq P_{G2} \leq 0.5$ p.u. Load demands are time dependent and are shown in Table 2 and Fig. 4. The parameters of the lines in the NASA benchmark system are listed in Table 3. The values of the load buses are given in Table 4.

The judgment matrix of PI_M for time $t1$–$t9$ is given in Table 5. The value of the matrix elements reflects the relative importance between every pair of operation time stages. These values were selected according to the engineer's knowledge and experience, using 9-ratio scale method.[5,6] For example, if experienced operators suggest that the value of decision making at $t2$ is more important compared with the value of decision making at $t1$, then the corresponding element in the judgement matrix should be 3. If both time stages $t4$ and $t5$ are thought to be equally important, the corresponding element in the matrix should be 1.

A unified ranking result that coordinates congestion indices PI_P, PI_V, and PI_M by using AHP is shown in Table 6 and Fig. 5. Both the values of PI_P and PI_V in Table 6 and Fig. 5 are normalized. The

Table 2 Daily system load demands in NASA benchmark system (p.u.)

Time stage	Time	P_{D3}	P_{D4}	P_{D5}	P_{D8}	P_{D9}	$\sum P_D$
$t1$	0.00–4.00	0.100	0.100	0.100	0.100	0.100	0.500
$t2$	4.01–6.00	0.122	0.122	0.122	0.112	0.112	0.590
$t3$	6.01–8.00	0.130	0.130	0.130	0.140	0.140	0.670
$t4$	8.01–12.0	0.150	0.150	0.150	0.160	0.160	0.770
$t5$	12.0–15.0	0.180	0.180	0.180	0.190	0.190	0.920
$t6$	15.0–18.0	0.210	0.210	0.210	0.260	0.260	1.150
$t7$	18.0–20.0	0.170	0.170	0.170	0.180	0.180	0.870
$t8$	20.0–22.0	0.125	0.125	0.125	0.120	0.120	0.615
$t9$	22.0–24.0	0.100	0.100	0.100	0.105	0.105	0.510

Table 3 Parameters of lines in NASA benchmark system (p.u.)

Line	R^{a}_{ij}	X^{a}_{ij}	$P_{ij\,\max}$	K_{ij}
1–6	0.015	0.0525	0.550	1.00
6–3	0.016	0.0560	0.250	0.50
6–4	0.012	0.0420	0.250	0.50
6–5	0.013	0.0456	0.250	0.50
1–7	0.014	0.0490	0.500	1.00
2–7	0.010	0.0350	0.550	1.00
7–8	0.013	0.0455	0.250	0.50
7–9	0.014	0.0490	0.250	0.50

[a]R_{ij} and X_{ij} are resistance and reactance of transmission line ij, respectively.

Table 4 Values of load buses in NASA benchmark system

Value[a]	Load 3	Load 4	Load 5	Load 8	Load 9
v_{ij}, \$/kW	150	200	180	190	220
α_{ij}	1.12	1.15	1.25	1.10	1.20

[a]Note v_{ij} are independent load values in a specific load bus and α_{ij} is absolute load priority to indicate the importance of each load.

eigenvalue of PI_M and its eigenvector are obtained from AHP. PI_M reflects the relative importance of different operation time stages. From Table 6, the final weighting coefficient of the time stage at $t6$ is given as 0.1489, which is defined as the maximum among all of the weighting factors. From the analysis, the system under study will be fully congested and will require the attention of the operational planning engineer when the system operates with a critical load and the generation value as shown in Fig. 5 at time 15.01–18.00 hrs.

Table 5 Judgment matrix of PI_M

PI_M	$t1$	$t2$	$t3$	$t4$	$t5$	$t6$	$t7$	$t8$	$t9$
$t1$	1	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{2}$	1
$t2$	3	1	2	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	2
$t3$	2	$\frac{1}{2}$	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	2
$t4$	4	2	2	1	1	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	3
$t5$	5	2	3	1	1	$\frac{1}{2}$	1	1	3
$t6$	5	3	3	3	2	1	3	1	4
$t7$	2	3	3	2	1	$\frac{1}{3}$	1	$\frac{1}{2}$	3
$t8$	2	3	3	2	1	1	2	1	2
$t9$	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	1

Table 6 Unified congestion rank for NASA benchmark system

Time stages	PI_P	PI_V	PI_M	Total weight	Total rank
$t1$	0.0867	0.0850	0.0413	0.0799	9
$t2$	0.1005	0.1097	0.0743	0.1000	7
$t3$	0.1102	0.1078	0.0575	0.1021	6
$t4$	0.1245	0.1262	0.1097	0.1231	4
$t5$	0.1316	0.1265	0.1401	0.1298	2
$t6$	0.1336	0.1342	0.2309	0.1489	1
$t7$	0.1225	0.1211	0.1335	0.1253	3
$t8$	0.9810	0.1037	0.1680	0.1098	5
$t9$	0.0891	0.0858	0.0444	0.0818	8

Table 7 Results of load shedding (λ = 20\$/MW ·h)

Variable	$t1$	$t2$	$t3$	$t4$	$t5$	$t6$	$t7$	$t8$	$t9$
x_3	1	1	1	0	0	0	0	1	1
x_4	1	1	1	1	1	1	1	1	1
x_5	1	1	1	1	1	1	1	1	1
x_8	1	1	1	1	0	0	1	1	1
x_9	1	1	1	1	1	1	1	1	1

Table 8 Results of load shedding (λ = 40\$/MW ·h)

Variable	$t1$	t2	t3	t4	t5	t6	t7	t8	t9
x_3	1	1	1	1	0	0	1	1	1
x_4	1	1	1	1	1	1	1	1	1
x_5	1	1	1	1	1	1	1	1	1
x_8	1	1	1	0	0	0	0	1	1
x_9	1	1	1	1	1	1	1	1	1

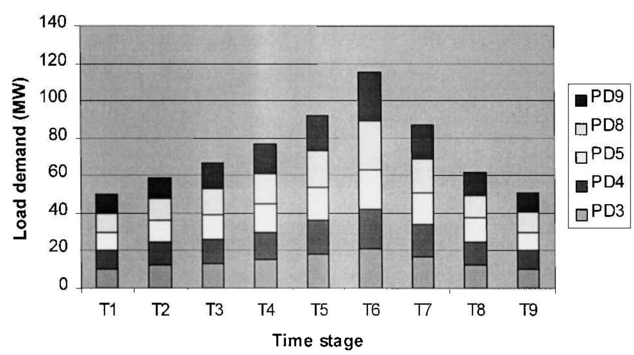

Fig. 4 Daily system load demands in NASA benchmark system.

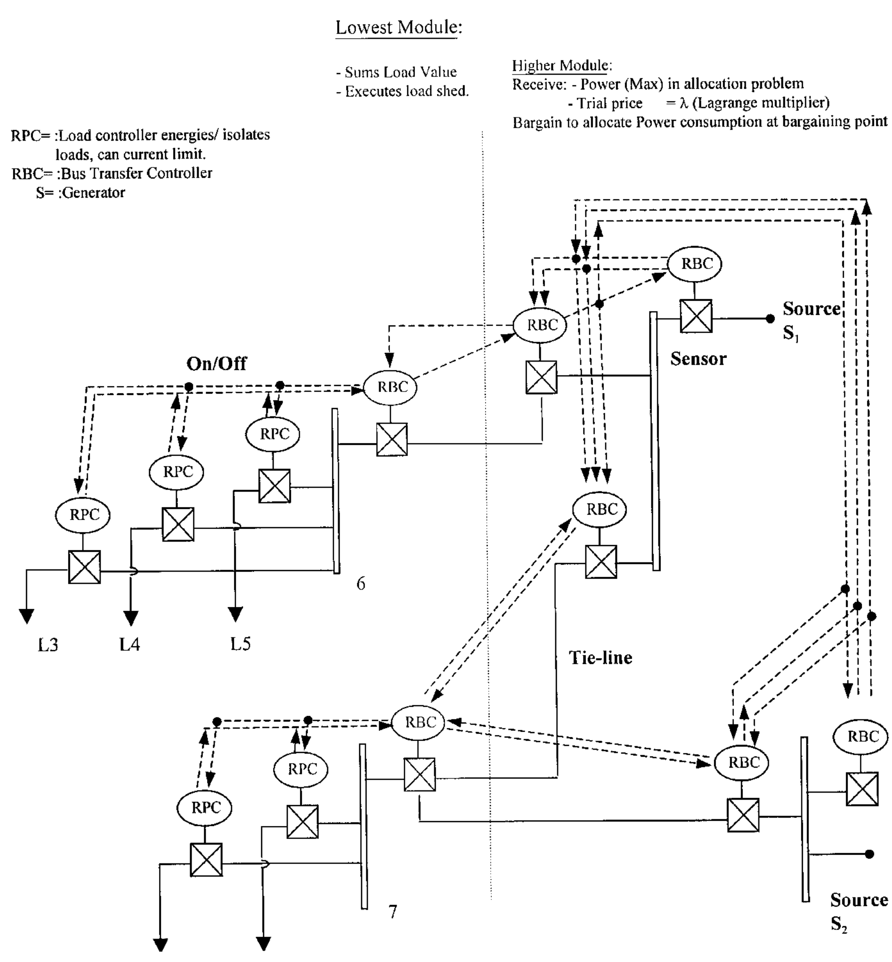

Fig. 3 NASA benchmark system topology.

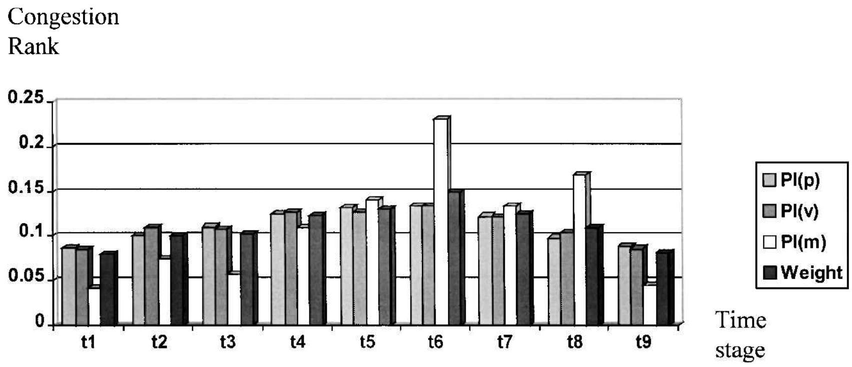

Fig. 5 Total ranking of system congestion during the operation period.

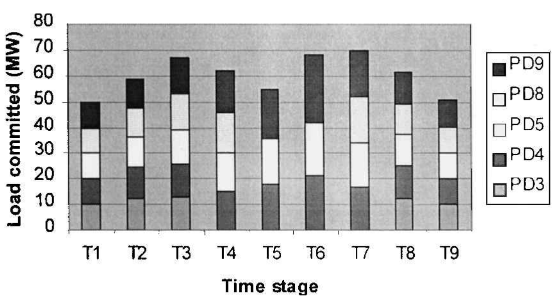

Fig. 6 Load shedding scheme for NASA benchmark system (λ = 20 $/MW ·h).

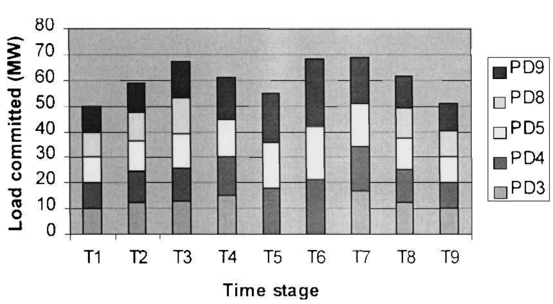

Fig. 7 Load shedding scheme for NASA benchmark system (λ = 40 $/MW ·h).

If power source 2 experiences an outage and the tie-line connecting sources 1 and 2 is closed, the total source power is 70 MW, which is less than load demands at time stages $t4$–$t7$. The load demands are between 77 and 115 MW during these time stages. Hence, the power supply is limited. The load-shedding calculation is conducted using the Everett method.[3] The final load-shedding scheme is shown in Table 7 and Fig. 6 (λ =20$/ MW · h) and Table 8 and Fig. 7 (λ =40$/MW · h). It can be seen from Tables 7 and 8 and Figs. 6 and 7 that load curtailment appeared at time stages $t4$, $t5$, $t6$, and $t7$. If the trial price λ is 20$/MW · h, load 3 is curtailed at time stages 4–7, and load 8 is curtailed at time stages 5 and 6. If the trial price λ is 40$/MW · h, load 3 is curtailed at time stages 5 and 6, and load 8 is curtailed at time stages 4–7.

Conclusions

The congestion and load-shedding problem in aerospace power system automation using the OPF, APH, and Everett optimization method is presented. The mathematical model of load shedding, in which the objective is payoff function, is devised. Two performance indices, circuit overload index and a system voltage problem index, are developed to evaluate the degree of system congestion for different operation time stages. These performance indices are obtained through the OPF calculation. The total ranking of system congestion for different time stages is conducted using the APH. The congested system is alleviated by the available controls such as load shedding and increase of transfer capacity of lines. The results can facilitate congestion management handling effectively in a typical aerospace power propulsion.

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