Load Shedding Algorithm Using Linear Programming for Congestion Problems by a Major Contingency

Ho-Sung Shin* **and Kyung-Bin Song**†

Abstract - Congestion problems of transmission lines are very important research issues in power system operations. Load curtailment is one of the ways to solve congestion problems by a major contingency. A systematic and effective mechanism for load shedding has been developed by investigating congestion distribution factors and the direct load control program. In this paper, a load shedding algorithm using linear programming for congestion problems by a major contingency is presented. In order to show the effectiveness of the proposed algorithm, it has been tested on the 6-bus sample system and the power system of Korea, and their results are presented.

Keywords: CDF (congestion distribution factor), Direct Load Control program, load shedding algorithm, transmission congestion

1. Introduction

Most of the electric power in Korea's power system flows from the southern area to Seoul, the capital city in the north. Electrical loads approximately 40% are consumed in the capital area and generation plants are mainly located in the southern portion of the country. Due to this characteristic, transmission congestion is a significant research issue. The transference of power from the south to the north is anticipated to be increased more and more in the future. Due to the increase in this flow pattern, transmission congestion has the potential to cause a serious voltage stability problem in the power system.

During transmission system planning, basic consideration involves securing the power systems for electric power demand levels, various operating points of generation outputs, contingencies and so on. In addition, transmission systems must also stay within the limits in the event of unplanned outages of transmission lines or transformers [1, 2]. Sufficient transmission capacities are needed to meet the operation condition within the limits in the event of unplanned outages. However, it is hard to provide sufficient transmission capacities overcoming engineering constraints such as thermal capacity limits of transmission lines, disturbances and faults in power systems, and social and economical constraints such as cost, environmental and social problems. Therefore, the possibility of transmission line congestion is ever present.

When the suppliers and consumers of electric energy desire to produce and consume in amounts that would cause the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested [1]. Modern power systems are required to maintain both high reliability and good power quality. Transmission congestions may bring about problems such as voltage instability and frequency instability. Therefore, management of this issue is primary concern within any country that has a power market [3, 4]. There are several methods to mitigate power system congestion, which include a change of the system topology, improvements of the line constant in transmission networks, expansion of transmission networks, constrained operations of generators in an operation point of view and so on. In order to solve the problem of transmission congestion, a method of the redistribution of generator outputs using line sensitivity was proposed [5].

Nevertheless, the system situation that can not operate the power systems normally without load shedding may occur. Specific contingencies may cause congestion problems that cannot be solved using normal methods. Therefore, a load shedding algorithm using linear programming in emergencies is presented in this paper. The loads for the load shedding are interruptible loads based on the contracted capacities of the direct load control program. The purpose of the proposed algorithm is to provide a solution to the transmission congestion in emergencies for major failures in the power system. In order to show the effectiveness of the proposed algorithm, it has been tested on the 6-bus sample system and the power system of KEPCO (Korea Electric Power Corporation).

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2. Load Shedding Algorithm

2.1 Objective function and constraints

There are several programs in load control. We are particularly interested in the direct load control program, which is a method of cutting demand side loads by a mutual contract between utilities and customers. The direct load control program has been managed by KEPCO (Korea Electric Power Corporation) and KEMCO (The Korea Energy Management Corporation) since 2002. In this paper, the load shedding algorithm using linear programming in an emergency can calculate the minimum amounts of interruptible loads to restore the power system to the normal operating state. The interruptible loads are based on the contracted capacities of the direct load control program. The mathematical formulation of the proposed algorithm is as follows:

$$Min \sum \Delta P_{Di} \tag{1}$$

Subject to:

$$\begin{gathered} \sum \Delta P_i = 0 \\ [S]\,\Delta P \le \Delta LF \\ -[B]\Delta\theta = \Delta P \\ \Delta P_{Gi}^{\min} \le \Delta P_{Gi} \le \Delta P_{Gi}^{\max} \\ 0 \le \Delta P_{Di} \le \Delta P_{Di}^{\max} \end{gathered}$$

Where, ΔP_{Di} : amounts of interruptible load at bus i

Where $i \in I_D$, I_D is a set of load bus

ΔP_i : $\Delta P_i = \Delta P_{Gi} - \Delta P_{Di}$

$[S]$: line sensitivity matrix in which the elements of the matrix are congestion distribution factors (CDF)

ΔLF : exceeded amounts of real power line flow limits

$[B]$: susceptance matrix of Y_{bus}

ΔP_{Gi} : variation values of generation output at bus i

Where $i \in I_G$, I_G is a set of generator buses

The solution of the optimization problem represented by Eq. (1) can be obtained using LP (linear programming) or nonlinear programming. The solution gives optimal generations at the generation buses and optimal loads at the load buses. The new obtained operating points do not violate the transmission line capacity limits and satisfy the power equation at all buses.

When a fault occurs in power systems, the proposed algorithm is basically applied. The flowchart of the proposed algorithm is described in Fig. 1.

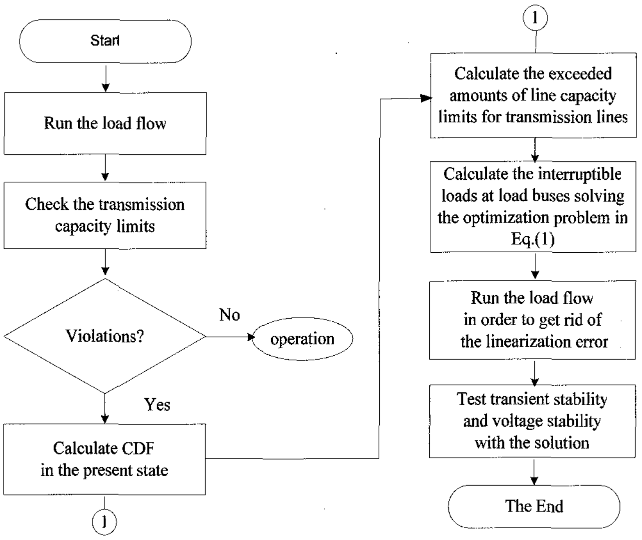

Fig. 1 Flowchart of the proposed algorithm

If the program starts, the program runs the load flow first. Transmission line capacity limits are checked for the interested transmission lines. If all transmission lines satisfy their capacity limits, the present state is maintained. Otherwise, it calculates CDF for the power system with the outage. Next, it calculates the exceeded amounts of transmission line capacity limits for transmission lines. In order to get rid of the violation of the transmission capacity, it determines the interruptible loads at load buses solving the optimization problem in Eq. (1). The linearization errors are reduced by running the load flow. Finally, it checks transient stability and voltage stability with the solution. If the power system is stable with the solution, the corresponding control scheme must be applied.

2.2 Line Sensitivity

In this paper, the CDF is used as a line sensitivity matrix, which represents the relations of transmission line flow and power injection in each bus in the power system. From the CDF proposed in [2], the priorities of load shedding in load buses can be determined. Derivations of the CDF are illustrated as follows. To define the CDF, start by defining actual power line flow using the lossless DC power flow formulation. The power flow on a transmission line connecting buses i and j is given as:

$$F^{(i,j)} = b_{i,j}(\delta_i - \delta_j) \tag{2}$$

Where $b_{i,j}$ is the susceptance of the transmission line linking bus i and j, and δ_i is the voltage phase angle of bus i.

This equation can be rewritten in a vector form as follows:

$$F^{(i,j)} = \{M^{(i,j)}\}^T \{\delta\} \tag{3}$$

Where $\{M^{(i,j)}\}$ is the sensitivity vector of the line power with respect to bus voltage phase angle changes whose elements are zeros except for the ith and jth , which are $b_{i,j}$ and $-b_{i,j}$ respectively. $\{\delta\}$ is a vector of the voltage phase angles of all buses including generators and loads.

Next, the equation describing the relationship between the bus voltage angles and real power injections for a n-bus network is given as follows:

$$\begin{bmatrix} P_1 \\ P_2 \\ \cdot \\ \cdot \\ P_n \end{bmatrix} = \begin{bmatrix} B_{1,1} & B_{1,2} & \cdots & B_{1,n} \\ B_{2,1} & B_{2,2} & \cdots & B_{2,n} \\ \cdot & \cdot & \cdot & \cdot \\ B_{n,1} & B_{n,2} & \cdots & B_{n,n} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \cdot \\ \cdot \\ \delta_n \end{bmatrix} \tag{4}$$

The detailed derivations are described in the appendix of [2]. Finally, congestion distribution factors (CDF) for the transmission line from i to j can be obtained as:

$$\{D^{(i,j)}\} = \{D_n^{(i,j)}\} + \beta^{(i,j)}\{1\} \tag{5}$$

Where

$$\beta^{(i,j)} = -\frac{D_n^{(i,j)}(i) + D_n^{(i,j)}(j)}{2} \tag{6}$$

The sign of the CDF at the bus indicates whether the power injection at that bus will increase or relive the congestion of the line of interest.

3. Case Studies

3.1 Case studies for the 6-bus sample system

The proposed algorithm has been tested on the 6-bus sample system which has 2 generators, 5 loads and 8 transmission lines. Power World Version 10.0 and PSSE Version 29.3 have been used as simulation tools for the load flow and check of stabilities. The configuration of the 6-bus sample system is shown in Fig. 2.

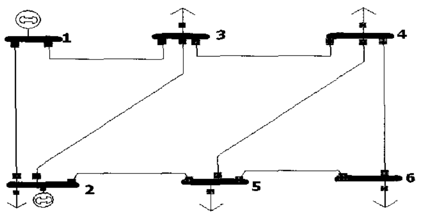

Fig. 2 Configuration of the 6-bus power system

The corresponding system data for the 6-bus system is presented in Tables 1and 2.

Table 1 Transmission line data

Line Number	Between Buses	Line Impedance		Maximum MW Flow
		R per unit	X per unit	
1	1-2	0.02	0.06	-
2	1-3	0.08	0.24	-
3	2-3	0.06	0.18	100
4	2-5	0.002	0.10	-
5	3-4	0.01	0.03	120
6	4-5	0.02	0.04	50
7	4-6	0.08	0.24	-
8	5-6	0.003	0.10	-

Table 2 Bus and load data

Bus Number	Voltage Magnitude	Load	
		Real (MW)	Reactive (Mvar)
1	1.06		
2	1.05	20	10
3	Not specified	45	15
4	Not specified	40	5
5	Not specified	60	10
6	Not specified	60	10

The bus voltages and power flows in steady-state are presented in Tables 3 and 4.

Table 3 Bus voltages in steady-state

Bus Number	Voltage Magnitude	Voltage Angle
1	1.060	0.00
2	1.040	-1.76
3	1.005	-6.53
4	1.002	-7.50
5	1.005	-7.52
6	0.993	-9.97

Table 4 Transmission line flows in steady-state

Line Number	Between Buses	Real Power	Reactive Power
1	1-2	61.53 MW	12.32 Mvar
2	1-3	53.55 MW	6.36 Mvar
3	2-3	50.11 MW	3.17 Mvar
4	2-5	105.07 MW	39.93 Mvar
5	3-4	55.15 Mw	-6.49 Mvar
6	4-5	-2.45 MW	-6.30 Mvar
7	4-6	17.30 MW	-4.09 Mvar
8	5-6	43.00 MW	11.81 Mvar

For the investigation, the transmission line limits for P_{23}, P_{34} and P_{45} are assumed as shown in Table 1. One of the severe transmission line outages is transmission line 4 between bus 2 and 5. The load flow results are presented in Tables 5 and 6.

Table 5 Bus voltages with the transmission line fault between bus 2 and 5

Bus Number	Voltage Magnitude	Voltage Angle
1	1.060	0.00
2	1.040	-0.79
3	0.878	-13.02
4	0.846	-16.57
5	0.815	-19.34
6	0.806	-22.09

Table 6 Transmission line flows with the transmission line fault between bus 2 and 5

Line Number	Between Buses	Real Power	Reactive Power
1	1-2	33.51 MW	20.97 Mvar
2	1-3	105.71 MW	52.18 Mvar
3	2-3	*128.20 MW	60.05 Mvar
4	2-5	0.00 MW	0.00 Mvar
5	3-4	*167.54 MW	41.55 Mvar
6	4-5	*94.36 MW	22.29 Mvar
7	4-6	29.31 MW	4.13 Mvar
8	5-6	31.74 MW	7.04 Mvar

*Transmission line flow violates its limit

For the investigation, three line flows (P_{23}, P_{34} and P_{45}) violate their transmission line capacity limits for the transmission line fault between bus 2 and bus 5. The proposed algorithm has been tested in two cases. One case is that having sufficient interruptible load and the other is that having limited interruptible load.

3.1.1 The case having sufficient interruptible load

When a fault occurs in transmission line 4 between bus 2 and 5, transmission lines 3, 5 and 6 violate their limits. In order to dispense with the violations, the proposed load shedding algorithm is applied. The solution is obtained by solving Eq. (1) using the linear programming method. The main results are as follows:

- 50 MW load curtailment at bus 5
- 50 MW generation down at bus 2

The load flow analysis is performed with the results of the interruptible load management algorithm. The power flows from the load flow analysis are satisfied with the constraints as shown in Table 7. As the results of Table 7 indicate, transmission line flows of the system are operated within the line flow limits respectively. In order to improve the bus voltage, the control of reactive power may be necessary.

Table 7 Line flows with the load shedding algorithm for the case having sufficient interruptible load

Line Number	Between Buses	Real Power	Reactive Power
1	1-2	44.38 MW	17.55 Mvar
2	1-3	78.60 MW	27.24 Mvar
3	2-3	88.95 MW	28.50 Mvar
4	2-5	0.00 MW	0.00 Mvar
5	3-4	112.60 MW	19.88 Mvar
6	4-5	47.74 MW	11.79 Mvar
7	4-6	23.39 MW	0.44 Mvar
8	5-6	37.18 MW	8.66 Mvar

3.1.2 The case having limited interruptible load

In fact, it is rare for a power system to have a sufficient interruptible load situation. Therefore, the system having the limited interruptible load has been tested. In this paper, interruptible load of load buses is assumed as half of real power as presented in Table 2.

In the similar procedure for the case having sufficient interruptible load, the proposed algorithm is applied to dispense with the violations and the solution is obtained as follows:

- 30 MW load curtailment at bus 5
- 28 MW load curtailment at bus 6
- 50 MW generation down at bus 2
- 8 MW generation down at bus 1

The load flow analysis is performed with the results of the load shedding algorithm. The power flows from the load flow analysis are satisfied with the constraints as shown in Table 8.

Table 8 Line flows with the load shedding algorithm for the case having limited interruptible load

Line Number	Between Buses	Real Power	Reactive Power
1	1-2	38.08 MW	19.52 Mvar
2	1-3	72.44 MW	22.68 Mvar
3	2-3	82.73 MW	22.32 Mvar
4	2-5	0.00 MW	0.00 Mvar
5	3-4	101.85 MW	14.12 Mvar
6	4-5	46.41 MW	8.05 Mvar
7	4-6	14.29 MW	-0.58 Mvar
8	5-6	15.91 MW	2.05 Mvar

If an improvement of voltage stability is needed, the process of reactive power compensation is performed to control the voltage profiles for the power system. There are two cases in the proposed algorithm; one is the case having sufficient interruptible load and the other is the case having limited interruptible load. The latter case is more practical than the former case in the power system. It is shown that the amounts of curtailed loads are equivalent in both cases, but the effects on the power system are quite different. In the proposed algorithm, the main idea is that the priority list of interruptible load buses is obtained using transmission line sensitivity to the buses with LP based on the optimization of load shedding.

3.2 Case Studies for the System of KEPCO

In order to investigate the proposed algorithm, it has also been tested on the existent power system of KEPCO. The configuration of the Korea power system is presented in Fig. 3 [6].

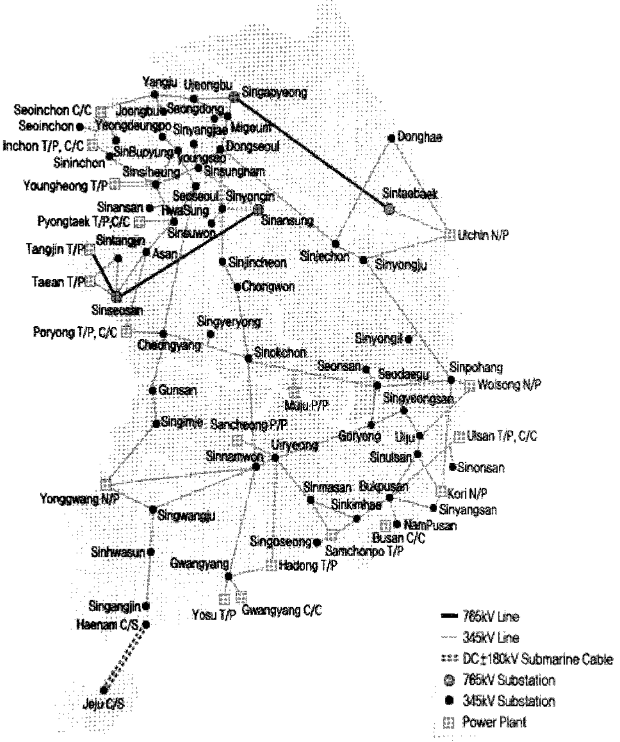

Fig. 3 Configuration of Korea's power system

In this paper, the estimated peak data in 2005 including the 2 circuits of the 765kV transmission line between Sintaebaek and Singapyeong is investigated for the case studies. The main summary of the estimated peak data in 2005 is presented in Table 9.

In the test data, the capital area loads include the loads of the Seoul, West Seoul, Suwon and Incheon areas in the load flow data of PSSE. The ratio of the capital area loads for the total load is approximately 40.8%. Most of the electric power in the power system of Korea flows from the southern area to the capital city of Seoul in the north, because generation plants are mainly located in the south area of Korea and many loads are concentrated in the capital area. Accordingly, it is necessary that the electric power flowing from the south area to the capital area should be investigated for several major contingencies. The actual power flowing in the interested transmission lines is presented in Tables 10 and 11.

Table 9 Summary of estimated peak data in 2005

Index	Contents	Remark
Total capacities of the generation	61,255 MW	
Total loads	53,168 MW	
Capital area loads	21,708 MW	
Total capacities contracted in Direct Load Control Program	2,098 MW	
Capital area capacities contracted in Direct Load Control Program	367 MW	
Number of the transmission line	1,295	
Number of the bus	765 kV	5
	345 kV	103
	154 kV	664

Table 10 Line flows between Jungbu and capital area

Bus	Bus	Volt.	From MW	From Mvar	Lim MVA
Hwaseong3	Asan3D	345	-1200	199	2191
Hwaseong3D	Asan3	345	-1257	223	2191
Sinanseong7	Sinseosan7	765	-1354	-116	7290
Sinanseong7	Sinseosan7	765	-1354	-116	7290
WestSeoul3	Cheongyang3D	345	-800	55	2191
WestSeoul3D	Cheongyang3	345	-958	126	2191
Sinyongin3	Sinjincheon3	345	-261	33	1095.
Sinyongin3	Sinjincheon3	345	-261	33	1095

Table 11 Line flows between Yeongdong and capital area

Bus	Bus	Volt.	From MW	From Mvar	Lim MVA
EastSeoul3	Sinjecheon3	345	-745	102	2191
EastSeoul3D	Sinjecheon3	345	-731	95	2191
Singapyeong7	Sintaebaek7	765	-1190	-59	7960
Singapyeong7	Sintaebaek7	765	-1190	-59	7960

As mentioned above in Tables 10 and 11, the actual power headed for the capital area is 11,308 MW, adding the real power flowing between the Jungbu area and the capital area and the real power flowing between the Yeongdong area and the capital area. It is shown that more than 50% of capital area loads are provided with electric power from Jungbu area and Yeongdong area. Electric demands are forecasted to increase continuously, and as such, the real power bound for the capital area will also rise. Moreover, the 765 kV transmission lines will be increasingly in charge of providing electric power to the capital area. Therefore, it is required that the prevented method on unplanned events such as outages of the 765 kV transmission lines to provide the stability of the power system be prepared. In the case of the outage in the 2 circuits of the 765 kV transmission line between Sinanseong 7 and Sinseosan 7, the results of load flow are also not converged. Therefore, when the transmission line is outaged, the real power of the main transmission lines is unknown. In order to know the real power of the main transmission lines, the line flows in the steady-state and the contingency-state after equal 5% curtailments in buses of capital area loads have been analyzed. The results are presented in Tables 12 and 13.

Table 12 Line flows in 5% curtailments of capital area loads

Bus	Bus	Volt.	From MW	From Mvar	Lim MVA
Singapyeon7	Sintaebaek7	765	-1160	-48	7960
Singapyeon7	Sintaebaek7	765	-1160	-48	7960
EastSeoul3	Sinjecheon3	345	-694	93	2191
EastSeoul3D	Sinjecheon3	345	-680	86	2191
Sinanseong7	Sinseosan7	765	-1301	-89	7290
Sinanseong7	Sinseosan7	765	-1301	-89	7290
Hwaseong3	Asan3D	345	-1108	192	2191
Hwaseong3D	Asan3	345	-1179	218	2191
WestSeoul3	Cheongyang3D	345	-705	34	2191
WestSeoul3D	Cheongyang3	345	-905	120	2191
Sinyongin3	Sinjincheon3	345	-186	23	1095
Sinyongin3	Sinjincheon3	345	-186	23	1095

Table 13 Line flows in contingency

Bus	Bus	Volt.	From MW	From Mvar	Lim MVA
Singapyeong7	Sintaebaek7	765	-1186	-91	7960
Singapyeong7	Sintaebaek7	765	-1186	-91	7960
EastSeoul3	Sinjecheon3	345	-781	81	2191
EastSeoul3D	Sinjecheon3	345	-759	70	2191
Hwaseong3	Asan3D	345	-1767	438	2191
Hwaseong3D	Asan3	345	-1910	489	2191
WestSeoul3	Cheongyang3D	345	-741	6	2191
WestSeoul3D	Cheongyang3	345	-1144	194	2191
Sinyongin3	Sinjincheon3	345	-546	101	1095
Sinyongin3	Sinjincheon3	345	-546	101	1095

As mentioned above in Tables 12 and 13, in the case of the outage in the 2 circuits of the 765 kV transmission line between Sinanseong 7 and Sinseosan 7, it is confirmed that over 50% of the real power flowing through the transmission line in steady-state flows through the 1 circuit of the 345 kV transmission line between Hwaseong 3 and Asan 3D and 1 circuit of the 345 kV transmission line between Hwaseong 3D and Asan 3. It is indirectly demonstrated that the results of load flow in the considered contingency are not converged. That is, two transmission lines between Hwaseong and Asan in the contingency are involved in transmission congestion problems. Moreover, whether the load shedding is necessary or not is determined according to the available capacities of transmission lines between Hwaseong and Asan and the actual power flowing through the transmission line between Sinanseong 7 and Sinseosan 7. In order to solve the congestion problems in two transmission lines between Hwaseong and Asan, the proposed algorithm is applied in this paper. The constraint of line flow in two congested transmissions is respectively determined as 50 MW considering the voltage stability condition and the amount of interruptible loads in each load bus is assumed as contracted capacities of direct load control program. The amount of load shedding is required by 211.8 MW, about 0.98% in capital area loads, and about 57.1% in contracted capacities of capital area loads. The amount of load shedding is able to be changed according to the constraints. The results in the application to the proposed algorithm are simulated by modifying the loads and generation outputs. The generation outputs are equally adjusted in 6 generators of the Taean 1G from 6G, which are the most sensitive to the transmission lines between Hwaseong and Asan. It is confirmed that the results in the simulation of load flow are normally converged, the voltage stabilities are satisfied and the interested line flows are flowing within the limit of each transmission line. The results of interested line flows are presented in Table 14.

Table 14 Line flows with the proposed algorithm

Bus	Bus	Volt.	From MW	From Mvar	Lim MVA
Singapyeong7	Sintaebaek7	765	-1117	-136	7960
Singapyeong7	Sintaebaek7	765	-1117	-136	7960
EastSeoul3	Sinjecheon3	345	-833	71	2191
EastSeoul3D	Sinjecheon3	345	-809	61	2191
Hwaseong3	Asan3D	345	-1841	384	2191
Hwaseong3D	Asan3	345	-1972	426	2191
WestSeoul3	Cheongyang3D	345	-827	30	2191
WestSeoul3D	Cheongyang3	345	-1193	165	2191
Sinyongin3	Sinjincheon3	345	-611	89	1095
Sinyongin3	Sinjincheon3	345	-611	89	1095

4. Conclusions

The load shedding algorithm is proposed to provide a solution to the transmission congestion from major outages in an emergency. The proposed algorithm can be applied in case of the system situation which cannot operate the power systems normally without load shedding. In the proposed method, the amounts of load curtailments are already contracted with customers by a direct load control program. In order to demonstrate the effectiveness of the proposed algorithm, it has been tested on the 6-bus sample system and the power system of Korea. Test results indicate that the proposed algorithm provides the minimal amounts of interruptible load to operate the power system normally solving the transmission congestion at the specific line corresponding to the major outage.

Acknowledgements

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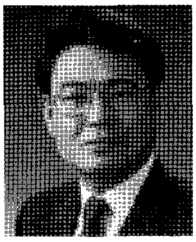

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