EXPERT SYSTEM FOR RESTORING TRUNK POWER SYSTEMS FROM COMPLETE SYSTEM COLLAPSE

BY

Naoto KAKIMOTO, Masayoshi EMOTO and Muneaki HAYASHI

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Abstract

In this paper, an expert system for restoring bulk power systems from complete collapse is proposed. The system secures an initial power source, integrates the trunk transmission system, and restarts all power stations. The rules were divided into several groups, and mainly used to control the flow of the restoration process. The detailed procedures were left to functions defined in Lisp. A partial knowledge, such as priorities in choosing an initial power source, in restoring power stations and substations, is read from data files. By adopting this method, system operators can adjust the restoration process so as to fit each individual power system without changing programs.

1. Introduction

With the increase in electric power demand, electric power systems become large and complex. Once a serious fault occurs in such a bulk power system, it is not easy to restore the system [1-4]. If it is a light power failure, its restoration may be carried out according to manuals provided in each substation. If not, the restoration must be left to experienced operators.

However, as systems become large and complex, burdens on operators get heavy. Mental factors accompaning system outages also make it difficult to do proper operations. There is also a social background that it is getting hard to obtain veteran operators, who need a long term training and much experience. Namely, the number of system outages decreases with the modernization of power systems and improvement in reliability, so operators rarely experience such operating situations.

Experienced operators make full use of operation rules and empirical

Department of Electrical Engineering

knowledge to determine a restoration plan. It is desired to develop a system which restores power systems by using this knowledge, or helps operators restore [5-11]. As one solution to this problem, expert systems are attracting a great deal of attention. The expert system stores knowledge on a given problem and makes inference with it to obtain a solution [12-19].

The expert system was initially thought effective for diagnosis and planning of subjects with no state transfer, and several studies have been made. The location of fault components is a typical example of the studies, and it has been partially put to practical use [15, 17]. By taking state transfer of subjects into consideration, the expert system has been applied to normal operations and fault restorations. The restoration of secondary power systems has been mainly studied, and several results have been reported [13, 14, 18, 19]. Recently, there is a trend to extend those results to the trunk transmission systems. On the other hand, trials have also been made to train operators by using stored knowledge and experience in the off-line mode [20].

In this paper, an expert system is proposed to automatically restore trunk power systems from complete collapse. It is rare that a fault develops in a system-wide outage since adequate investigations have been made on system configurations and system protections. However, it is prudent to imagine a complete collapse of a system due to unexpected factors, and to establish a method of restoring the system quickly and safely, if we recall some examples which occured in New York and France.

The outline of the proposed expert system is first described. The adopted restoration plan and concrete steps for restoring power systems from complete collapse are described next by using several examples. Lastly, some evaluation of the expert system is made and the remaining problems are described.

2. Outline of system

The outline of the proposed expert system is given in this chapter. The system carries out the restoration of a power system from its total collapse. The structure of the system is first shown. The object power system and its representation are described next. Lastly, the specification of the expert system is described.

〈2. 1〉 System Structure

Fig. 1 shows a structure of this expert system. The parts enclosed by single frames are programs, and the ones enclosed by double frames are data. The

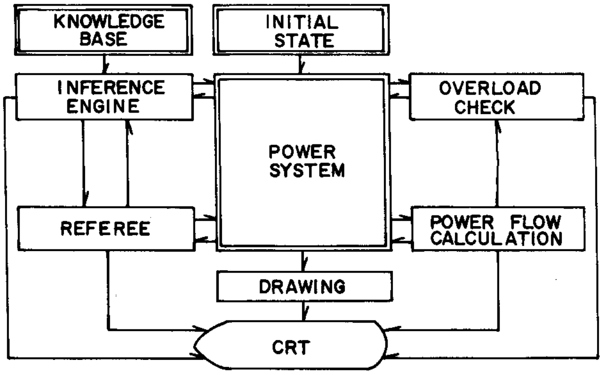

Fig. 1 Structure of expert system.

system consists of three main parts, namely, a part for generating a restoration process, a part for carrying the load flow calculation and checking overloads, and a part for displaying power systems.

1) Part for generating restoration process

This part consists of an inference engine and a knowledge base, which were designed with an expert shell called Eshell [21]. The inference engine produces restoration operations most appropriate to a given power system state by referring to the knowledge base. Every generated operation is checked by a Referee as to whether or not there is a problem on its execution. If an operation is executable, it is carried out and the next operation is tried. If there is any problem, such as overloads, the operation is discarded, or supplementary operations are generated.

2) Load flow calculation and overload check

This part carries out load flow calculations when the power system state changes due to switching operations, and checks all transformers and transmission lines in a power system for occurrence of an overload. The program for the load flow calculation is written in Fortran, while other programs are written in Lisp. The calculation is carried out by transferring data between those programs. By adopting this mode, complex numerical calculations are conducted with high efficiency.

3) Display of power system

This part displays on CRT a part of a power system where restoration operations are proceeding. The power system extends in a wide area, so the whole system is not displayed at one time, but only the part where relevant operations are being made is shown. The color of the machine which is operated turns red, so it is possible to certify operations on CRT. Operations in normal states are done with a mouse.

⟨2. 2⟩ Object power system

Fig. 2 shows a power system which is treated as an object in this paper. This system is a trunk system of 500 kV and 220 kV. There are 7 power stations, 25 substations, and about 1300 machines in this system.

The machines are transmission lines, buses, circuit breakers, line switches, transformers, etc. Those machines have their own data items, which are listed in a table. Data on the machines are all stored in a file. The data are read from the file according to the table showing the items at the beginning of restoration, and are transformed into property lists.

If some information on a machine is necessary, it is obtained by checking the property list of the machine, as follows;

```
(get 'cb01 'id      )······>cb
(get 'cb01 'voltage )······>500kV
(get 'cb01 'primary)······>ls01          (1)
(get 'cb01 'state   )······>on
```

where "get" is a function to obtain a property value of an object. Namely, a machine cb 01 is a circuit breaker, and its voltage is 500 kV, its primary connection is a machine ls 01, and it is now closed. This representation of machine data has several advantages as follows;

Firstly, this representation of the system is close to the one which people have in mind. Name, parameters, and connections of each machine have been represented as they are, so they are very easy to understand. This is clear if we imagine representing connections of machines with a matrix. By using this representation, actual power system data are easily obtained by computer programs, and easily modified.

The second advantage is that the representation is easy to extend. It is only necessary to add a data item in the table, and to write the corresponding data in the data file. No change of programs is required.

⟨2. 3⟩ Inference mechanism

An inference mechanism called the blackboard model is adopted in this expert system [21]. The model consists of knowledge sources and a blackboard as shown in Fig. 3.

The knowledge sources form the knowledge base in Fig. 1. Each knowledge source has a group of rules, which is designed so as to take charge of a part of

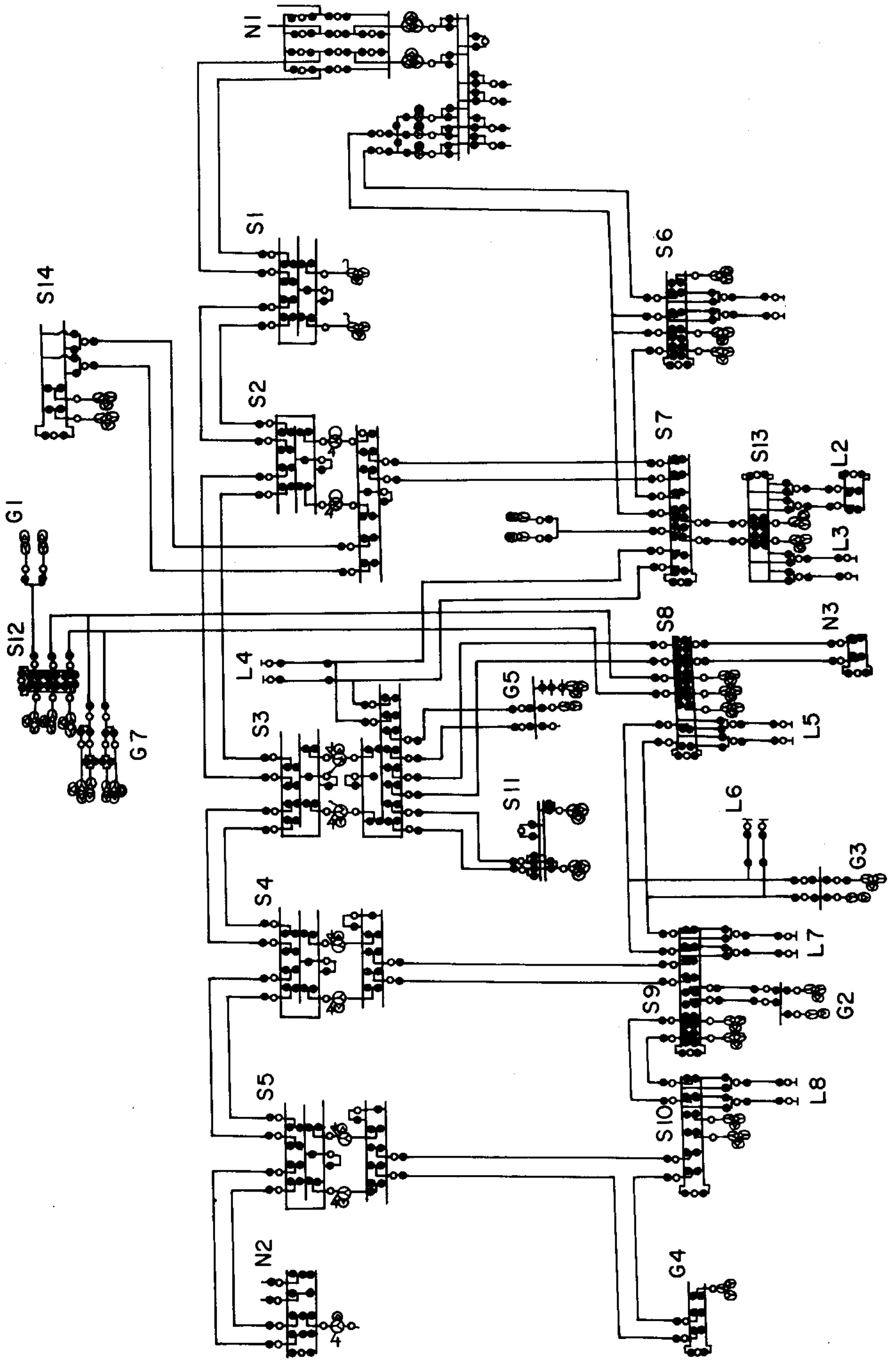

Fig. 2 Object power system.

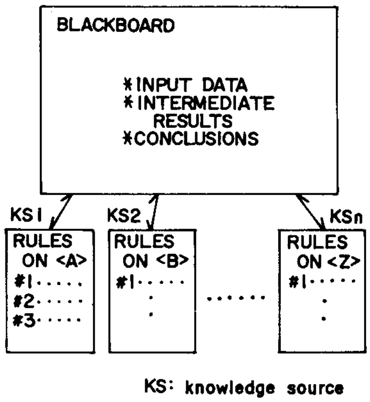

Fig. 3 Blackboard model.

the restoration process. The rules are all production rules, i. e.,

$$\textit{If} \ldots\ldots, \textit{then} \ldots\ldots \qquad (2)$$

The sources consist of these simple units, which make it easy to construct and modify them.

The blackboard is a common data area used to store input data, intermediate results, and conclusions. The results obtained in one knowledge source is transferred to another knowledge source through this common area.

The inference engine switches the knowledge source one after another according to the problems to be solved. One source is therefore referred to at one time. Only rules relevant to a present problem are searched, which contributes to improving calculation efficiency.

The expert system of this paper has 23 knowledge sources. Those are used to secure an initial power source, to determine an order to restore power stations, to choose a restoration route, and to generate concrete switching operations, etc. The number of rules included in the knowledge sources is 91. The average number of rules in one knowledge source is about 4. These rules are mainly used to control the flow of the restoration process. Detailed works are performed with many programs written in Lisp.

3. Restoration Process

〈3. 1〉 Flow of restoration process [1, 2]

As soon as a system outage occurs, much information is gathered in a load dispatching center through indicators and communications. The operators of the center promptly grasp the system state with the information. They determine a restoration plan by considering the power outage area and the states of other adjacent systems, and carry out the plan. Fig. 4 shows the flow of the restoration process used in this expert system.

If a system outage happens, all predetermined circuit breakers in blackout power and substations are opened first to avoid recollapse of the system due to load inrushes or voltage rises. An initial power source is secured next by receiving power from adjacent power systems or power stations with blackstart

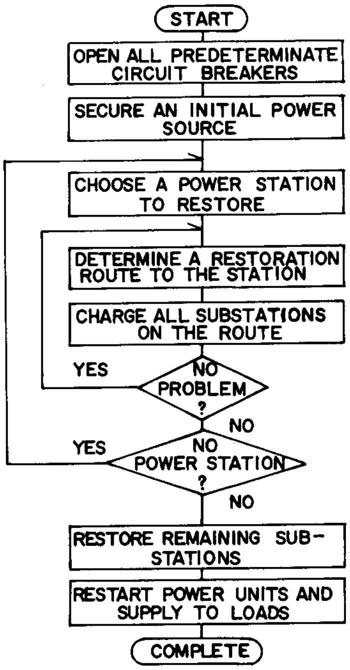

Fig. 4 Flow of restoration process.

capability. One power station is chosen to restore. The power stations are preferentially restored because station services must be supplied first to restart them. One restoration route from the initial source to the power station is determined. All the substations on the route are charged one after another to the power stations. If the restoration of all power stations is completed like this, then the remaining substations are restored next. If the power stations are restarted, they are interconnected to the system, and loads are picked up from the important ones. These restoration steps are explained in detail in the following sections.

This expert system treats a power system as one unit. However, one power system is often sectionalized into two or more subsystems, and the subsystems are restored simultaneously. The expert system is applicable to those cases, too, if we regard one subsystem as a power system.

〈3. 2〉 Operation right after system outage

There is a rare case where a transient fault is not held to a limited area, but extends to a considerably wide area. In extreme cases, power outage extends over a whole system. The system operators immediately start restoration of the system. First of all, they open all predeterminate circuit breakers of all substations in order to avoid excessive deviations due to an inrush of loads.

These switching operations are also carried out in this expert system. For this purpose, information on the circuit breakers to be opened is required. This information is provided from a data file.

Fig. 5 is a simplified diagram of Fig. 2, and it represents the state of the power system after the switching operations. The substations have been mutually separated by opening the circuit-breakers at the ends of the transmission lines.

〈3. 3〉 Initial power source

An initial power source is determined next, following the switching opera-

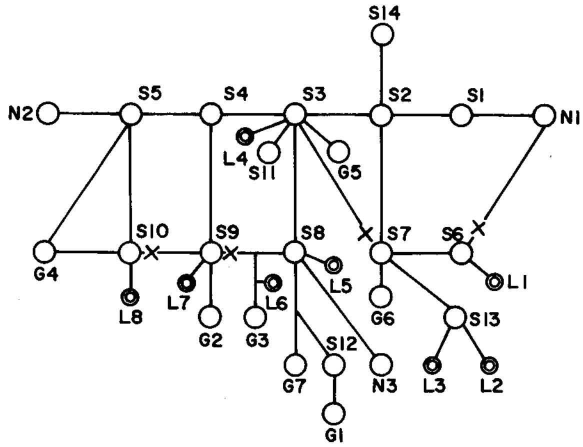

Fig. 5 Power system after complete collapse.

tions. There are two ways of obtaining the initial sources. One is to receive power through tie lines from the adjoining power systems. The other is to start generating plants with black-start capability.

Recent power systems are interconnected with each other. If it is possible to receive power from one of the adjoining power systems, the system is used as the initial source. The restoration proceeds by energizing transmission lines with the adjoining system as the starting point. If no adjoining system is available, one of the power stations with black-start capability is used as the initial source. It takes about 30 - 60 minutes to start these stations.

Power or substations which suit this purpose are selected, and their names are registered in a file. The names are read from the file, and are displayed on the CRT. When determining the initial source, one of these candidates is chosen.

The power system of Fig. 5 has three adjoining power systems. Substations N 1, N 2, and N 3 are those adjoining systems, respectively. Besides the substations, there are two hydropower stations with black start capability, that is, G 6 and G 7. The rank of these stations as an initial power source is set as follows;

1. $N1$
2. $N2$
3. $N3$ (3)
4. $G6$
5. $G7$

As an example, assume that N 1 with the highest priority is available, and select it as initial power source.

〈3. 4〉 Restoration order of power stations

If an initial power source is chosen, the next step is to choose a power station to restore. There are usually several power stations in a power system, so it becomes a problem to determine an order of restoration. This expert system gives ranks of priority to power stations, and restore from power stations with a higher priority. The priority is determined according to the kind and state of power station. Namely, the priority depends upon whether the power station is hydro, thermal, or nuclear, and upon whether it is running or stopped.

If a generating unit keeps running by supplying its station service after a system outage, it can be readily interconnected. Hence, its restoration time is very short. However, this running state does not last a long time, and the unit must be placed back into operation within a short time interval. Otherwise it stops, and a restart is not possible for several hours. Such a time interval then is very critical to the restoration, particularly in those stations where station service must be supplied from another station. These power stations are given higher priorities than those which have stopped.

If a running nuclear unit stops because of a delay in reinterconnection, it takes about 36 hours to regain a full load. Hence if the unit is running, it must be interconnected to the system with the highest priority. In such cases where the unit unfortunately stops, it is desirable to supply station service as fast as possible because an increase in Xe also delays the restart of the unit further about 10 hours.

If a thermal unit stops, several hours are required to reach its full load. Whether a vacuum of the thermal condenser is kept or not, also affects the restoration time by about 1 hour. The vacuum is kept for 20 – 80 minutes after the boiler trips. It is desirable to supply station service for the restart as fast as possible.

It is comparatively easy to keep hydro power stations in a running state after a system outage. Even if it stops, its restoration is easy and does not take so long a time, so hydro units do not impose strict restrictions on the restoration. The priority of hydro units is ranked in lower levels.

If a power station has a black-start capability, it can restart independently after a system outage. The power station supplies its own station service and near loads till it is interconnected to the restored power system. These power stations are ranked in the lowest level.

From the above consideration, the priority in restoring power stations is set as shown in Table 1. Restoration proceeds from generators with higher priorities. No particular order has been set for power stations with the same rank, but it is easy to introduce an order, for example, according to generation capacities. Of course, the order of priority is not fixed, but can be changed with each power system.

Table 1. Priority in restoring power stations.

Rank	Type	State	Generators	p*
1	nuclear	running	G1	1.0
2	thermal	running	G2, G3	0.8
3	thermal	stopped	G4, G5	0.6
4	nuclear	stopped	......	0.4
5	hydro	running	G7	0.2
6	hydro	stopped	G6	0.0

* : priority is thus quantified in this system.

The generators in the table correspond to those in Fig. 5. There are 1 nuclear power station, 4 thermal power stations, and 2 hydro power stations. In this example, the nuclear power station G 1 is running, so it has the highest priority. Two thermal stations G 2, G 3 are running, and two others G 4, G 5 have stopped. G 2, G 3 belong to rank 2, and G 4, G 5 to rank 3. Hydro stations G 6, G 7 have rank 6, 5, respectively. The restoration proceeds in the order of G 1, G 2, G 3, G 4, G 5, G 7, G 6.

〈3. 5〉 Restoration route

1) Restoration route search

Once a power station to restore is determined, a route to the power station is next sought since there are several routes between the initial power source and the target power station. All the routes of the substation level are enumerated. There are 16 routes connecting the initial source N 1 and the target station G 1 in Fig. 5. These routes are put in order according to the length of the route. The shortest route has the highest priority. Fig. 6 shows one of the shortest routes, i. e.,

$$N1\text{-}S1\text{-}S2\text{-}S3\text{-}S8\text{-}S12\text{-}G1 \qquad (4)$$

from N 1 to G 1. This route has been selected so as to connect the stations through normally used transmission lines. There is another short route, i. e.,

$$N1\text{-}S6\text{-}S7\text{-}S3\text{-}S8\text{-}S12\text{-}G1 \qquad (5)$$

which goes via substations S 6 and S 7. However, N 1 and S 6, S 7 and S 3 are not connected in the normal state, so the priority of this route is lower than that of the route in (4). Namely, the restoration route should be closest to the

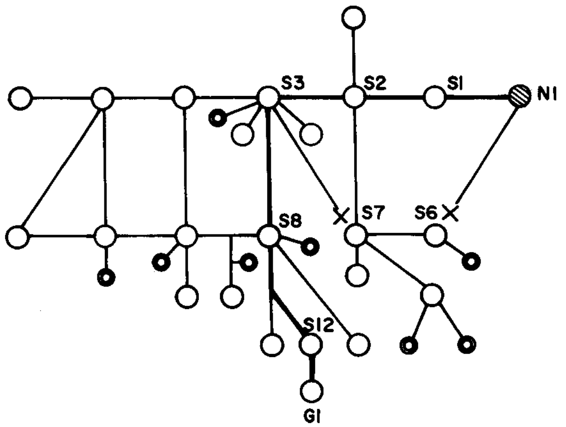

Fig. 6 Restoration route from N 1 to G 1.

normal one as well as to the shortest.

2) Energization of restoration route

If a restoration route is determined, the next step is to energize it with the initial power source. The energization of the route proceeds from one station to another station.

In order to restore the target power station, it is necessary that the adjoining substation on the route has been energized. It is checked whether the substation has been energized or not. In the example of Fig. 6, S 12 is first checked. If the substation has been charged, then the target station G 1 is directly energized from S 12. On the other hand, if S 12 has not been charged, the energization of the target station must be delayed till the substation is charged. The substation S 8 is next checked to energize S 12. This check is iterated till an energized substation is found.

All the substations on the route in Fig. 6, have not been energized at the beginning of the restoration. The initial source N 1 is only one energized substation. The substation S 1 is energized from N 1 first, and S 2 is energized from S 1, next. This procedure is iterated for S 3, S 8, S 12, and lastly G 1. After all the substations on the route are energized like this, the target power station G 1 is connected with S 12.

〈3. 6〉 Connection of substations

Several switching operations are required in order to energize one substation from another station through transmission lines. Only one of two circuits is often preferentially restored for quick restoration in practical systems, but both of them are restored at a time, in this expert system for simplicity.

1) Restoration course search

The buses in the substations are first identified. Fig. 7 shows substations S 2 and S 3. There are four buses in each substation, respectively. All the buses in S 2 have already been charged, while none of the buses in S 3 has been charged. There are several courses to connect those buses, where courses through other substations are not considered.

The courses all go through one of the transmission lines connecting the substations, e. g., line 1 and 2 in Fig. 7. The courses are hence found as follows. Choose first one of the transmission lines, e. g., line 1, and consider charging this line with the buses in S 2. Buses 3 and 4 are counted out because they are connectable only through the already charged buses 1 and 2. Namely, the courses through transformers are not adopted. There are 2 courses to connect bus 1 or 2 with line 1, and the shortest one is adopted.

bus 1-*ls*13-*cb*03-*ls*03-*line* 1······*s*1
bus 2-*ls*23-*cb*03-*ls*03-*line* 1······*s*2 (6)

The course to charge line 1 from S 2 has been found, so consider next to energize the buses of S 3 with this line. Similarly, there are two courses as follows.

line 1-*ls*01-*cb*01-*ls*11-*bus* 1······*r*1
line 1-*ls*01-*cb*01-*ls*21-*bus* 2······*r*2 (7)

The courses to bus 3 and 4 are all excluded, again. The courses through line 2 are also obtained in a similar way.

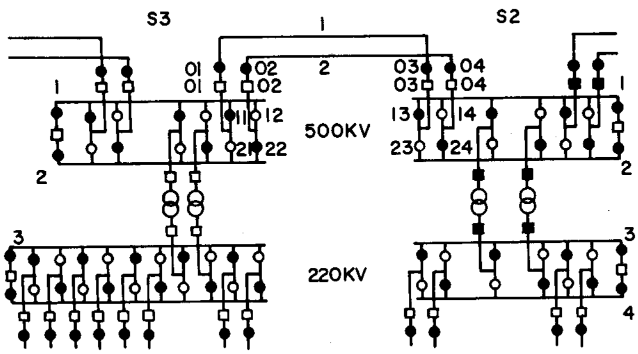

Fig. 7 Connection of two substations.

2) Selection of course

The courses in (6) and (7) have been ordered according to a priority. In this expert system, the number of required switching operations determines the priority of the course. Namely, a course with fewer open switches has higher priority.

For example, three switches are on the two courses of (6). One is a circuit -breaker, and the others are line switches. The switches cb 03 and ls 03 are common to both courses. However, the line switch ls 13 is closed while ls 23 is open. Namely, the second course needs two switching operations while the first need only one. The first course is adopted, and line 1 is charged from bus 1 of S 2 through course s 1.

In a similar way, the first course r 1 in (7) is chosen to charge bus 1 of S 3 from line 1. Combining s 1 and r 1, bus 1 's in S 2 and S 3 are connected as follows;

bus 1–*ls*13–*cb*03–*ls*03–*line*1–*ls*01–*cb*01–*ls*11–*bus* 1
(*S*2) (*S*2) (*S*2) (*S*2) (*S*3) (*S*3) (*S*3) (*S*3) (8)

Once a bus is charged through a course, the course is eliminated from the candidates. All courses which use machines in common with the adopted one, are also eliminated. For example, all courses through line 1, i. e., those in (6) and (7), are eliminated. A course is then chosen among the remaining courses through line 2 in order to charge bus 2 of S 3. The course is,

bus 2–*ls*24–*cb*04–*ls*04–*line*2–*ls*02–*cb*02–*ls*22–*bus* 2
(*S*2) (*S*2) (*S*2) (*S*2) (*S*3) (*S*3) (*S*3) (*S*3) (9)

The circuit-breakers cb 04 of S 2 and cb 02 of S 3 on this course are closed.

3) Switching operations

There are several open switches on an adopted course. In order to charge a target bus, it is necessary to close those switches. The switches are usually closed in sequence from the source side.

There are two kinds of switches, namely, circuit breakers and line switches. Circuit breakers are able to open and shut the current, but line switches are not. The operation of a line switch, through which current is flowing or flows after the operation, is not allowed. This check is made by the Referee in Fig. 1. In these cases, a specified circuit breaker is opened first. The line switch is then closed. The opened circuit breaker is closed again.

If all line switches have been closed, switching operations are made on circuit breakers, next. The breakers are operated in sequence from the source side, too. Some of them are often interlocked by other switches to avoid mis-operations. This check is also made by the Referee. In those cases of interlock, the related switches are first operated, and the circuit breaker is closed.

The course of (8) includes four line switches and two circuit breakers. The line switches are already closed. The circuit breakers are closed in sequence of cb03 of S2 and cb01 of S3. By these operations, bus 1 of S3 is charged. Similarly, cb04 of S2 and cb02 of S3 are operated to charge bus 2 of S3.

4) Confirmation of energization

Switching operations on an adopted course energize a target bus. However, those operations change the state of the power system. A power flow calculation is carried out to examine whether each bus in the object substation has been charged or not.

If all buses in the substation have been charged without any overloads, then the energization of the substation is completed.

If there is any overload, another course is chosen among the remaining courses and examined. If the overload is not still resolved after all these efforts, the adopted restoration route is judged to be inappropriate, and another route is investigated.

If no course is remaining, which means that all courses are exhausted, then the operations to connect two substations end. Operations in a target substation are carried out next. Bus 1 and 2 of S3 have been charged, but bus 3 and 4 have not been charged yet. There is no course to directly charge them from S 2, however. The operations between the substations end. The remaining buses are charged by operations in the substation.

〈3. 7〉 Operations in a substation

If some buses of the target station could not be charged from the source station, the buses are charged from the already charged buses of the same station.

Two cases are considered in charging a bus. If another bus of the same voltage level has been charged, a bus-tie switch is closed to charge it. If not, the bus is charged from another bus of a different voltage level through transformers.

All courses from a target bus to charged buses are first found. The courses which go outside of the station are excluded. Among these courses, the ones through bus-tie switches are extracted, and the one with the fewest switching operations is adopted. If it is not possible to charge the target bus by using the

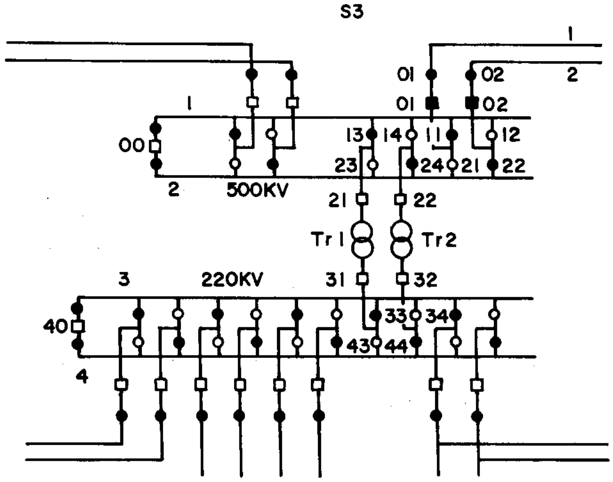

Fig. 8 Operation in substation.

courses, charging from different voltage level buses is tried. In this case, courses through transformers to already charged buses are extracted, and one of them is adopted. In these operations, the courses used once are eliminated to avoid overloads due to the concentration of power flow.

As an example, consider Fig. 8. Buses 1 and 2 have been charged. There are two noncharged buses, namely, buses 3 and 4. Since the voltage levels of buses 1 and 2 are different from those of buses 3 and 4, it is impossible to connect them with bus-tie switches. The charging of buses 3 and 4 must be done through transformers. There are many courses for connecting buses 1, 2 with 3, 4. The shortest course from either bus 1 or 2 to bus 3 is

$$bus\ 1\text{-}ls13\text{-}cb21\text{-}Tr1\text{-}cb31\text{-}ls33\text{-}bus\ 3 \qquad (10)$$

This course is adopted to charge bus 3. The two switching operations of cb 21 and cb 31 are carried out. Usually, line switches are not operated right after the system outage, so restoration to the normal state seems to be realized by adopting a course with the fewest operations. As for bus 4, a course

$$bus\ 2\text{-}ls24\text{-}cb22\text{-}Tr2\text{-}cb32\text{-}ls44\text{-}bus\ 4 \qquad (11)$$

is adopted, which is the shortest one among the remaining courses. By these operations, all the buses in S 3 are charged. Hence, the energization of S 3 is completed. The next step is to energize substation S 8 by using this substation as a power source.

〈3. 8〉 Check of restoration

Three cases are considered to happen in restoring a power station along an adopted route.

If a power station is restored through an adopted route, its restoration succeeds. The state of the power system is saved in a file. This file is used to place the system back to the state when the next step fails. If there are some blackout power stations, one of them is restored next, which is chosen according to the order of priority. If there is no blackout power station except for substations, then those substations are restored next. If a restoration route is judged to be not appropriate because of unresolved overloads, etc, then it is discarded. The power system state is returned to that before the restoration along the route began. Another route is then sought to restore the target power station. The route is chosen among the routes which do not go through the places where the overloads appeared. If there is any route satisfying this restriction, then it is adopted. If no route is remaining, then the restoration of the power station is judged to be a failure.

If a power station was not restored well, then its restoration is given up. The state of the power system is returned to the original state. The power station is eliminated from the candidates for restoration. A new power station to restore is chosen according to the order of priority.

As an example, consider the first case. In Fig. 9, the power station G 1 has been successfully restored along the route chosen in Fig. 6. Hence, a thermal power station G 2 is restored next. One of routes from N 1 to G 2,

$$N1\text{-}S1\text{-}S2\text{-}S3\text{-}S4\text{-}S9\text{-}G2 \tag{12}$$

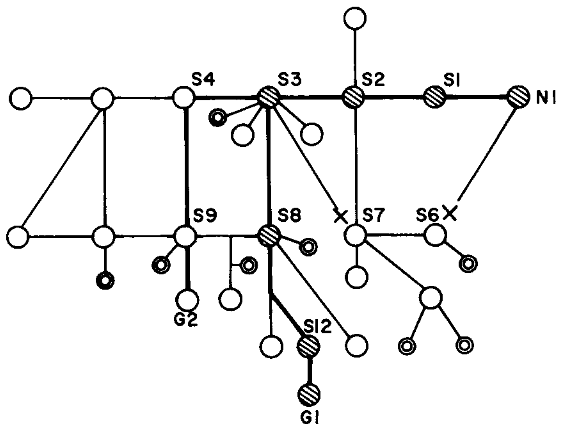

Fig. 9 Restoration of power station G 2.

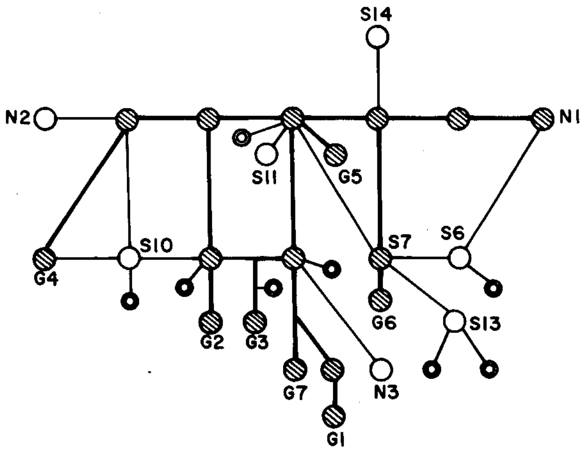

Fig. 10 Restoration of all power stations.

is used to energize G 2. As for substations S 1, S 2, S 3, they have been energized in the process of restoring G 1, though S 4, S 9, and G 2 have not been restored, yet. The restoration proceeds from S 3 to S 4, from S 4 to S 9, and from S 9 to G 2. The station service of G 2 is then supplied. This operation is iteratively applied to other power stations in the order of priority. Fig. 10 shows the state of the power system at the time when all power stations have been restored.

〈3. 9〉 Restoration of remaining substations

At this point of time, all power stations have been restored, and several substations on the adopted routes to the power stations have been restored, too. The restoration proceeds to the other remaining substations.

One of the substations is chosen according to an order of priority. If there are charged substations adjoining the chosen substation, then one of them is selected as the power source. The source station should be one connected in the normal state as far as possible. Switching operations are made to connect the stations. If no adjoining substation has been energized, then the restoration of this station is left over, and another substation is restored first. By iterating these operations, all substation are restored.

The priority in restoring substations is chosen as shown in Table 2. The 500 kV substations have the highest priority. The priority of 220 kV substations depends on the place where they are located. Those for loads are given lower priorities. Interconnection with the other power systems are done after all substations in the system have been restored.

Table 2. Priority in restoring substations.

Rank	Type	Substations	p*
1	500kV	S1, S2, S3, S4, S5	1.0
2	220kV	S6, S7, S8, S9, S10	0.8
3	220kV	S11, S12, S13, S14	0.6
4	220kV	L1, L2, L3, L4, L5 L6, L7, L8	0.4
5	500kV	N1, N2	0.2
6	220kV	N3	0.0

* : Priorities are thus quantified in this system.

Several substations have been restored in the process of restoring power stations, as shown in Fig. 10. The restoration of 500 kV substations has been completed. Among the 220 kV substations of rank 2, S 6 and S 10 have not been energized. The restoration of these substations is first done. The substations S 11, S 13, S 14 of rank 3 have not been energized yet. All substations of rank 4, 5, and 6 have not been charged, except for N 1 which was used as the initial source. These substations are restored one after another according to the order of priority. As an example, consider that S 6. N 1 and S 7 are adjoining this substation. It is checked whether they are charged or not. Both of them have been charged in this case, and S 7 is used to energize this substation. If they are not charged, this substation is left over, and another substation S 10 is restored first.

Fig. 11 shows the state of the power system after all substations have been restored. Substations S 5 and S 10 have not been connected, but are connected in the normal state. Some operations are added to connect them.

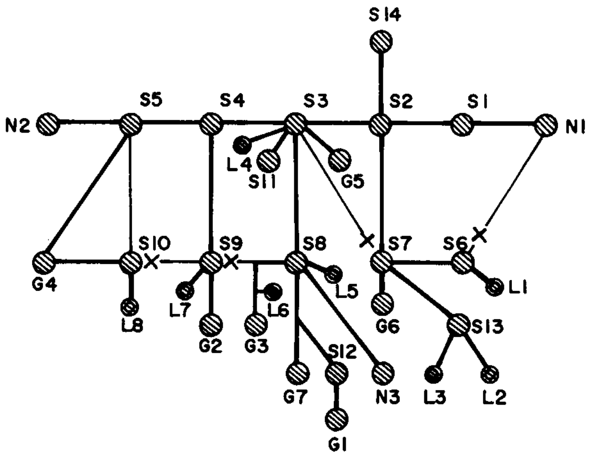

Fig. 11 Restoration of remaining substations.

4. Conclusions

In this paper, an expert system for automatically restoring power systems from complete collapse was proposed. The system has several features summarized as follows;

1) The knowledge base consists of 23 knowledge sources. One knowledge source has about 4 rules on average, and those rules are mainly used to control the restoration process. Detailed works are processed with programs written in Lisp.

2) Data peculiar to each individual power system, such as parameters of machines, normal states of switches, initial power sources and priority orders of power and substations, are all read from data files. This method serves to keep the generality of the expert system. By changing these data, system operators can adjust this expert system to a particular power system without changing programs.

3) The program for load flow calculations was written in Fortran, while other programs were written in Lisp in order to cope with complex numerical calculations. Data transfers between those programs were made through files, too.

4) The part of the power system where operations are being carried out, is displayed on CRT. Each operation is visualized by changing the color of the object machine. This function serves to trace restoration operations.

This expert system was applied to an example power system, and was checked in each restoration step. It was certified that the system works as designed.

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