Proc. Natl. Sci. Counc. ROC(A)
Vol. 20, No. 5, 1996. pp. 564-572

The Implementation of a Power System Restoration Simulator

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(Received December 21, 1995; Accepted March 2, 1996)

ABSTRACT

Due to the increasing demand for higher service quality, utilities have devoted themselves to improving of power reliability and stability. In the wake of many large scale blackouts around the world, power system restoration strategies are under intensive study because of the impact of power interruptions on the economy and customers' perception of utilities' service quality. In this paper, a prototype power system restoration simulator is presented. In this simulator, stage restoration strategies, heuristic rules and analytical tools are used to determine the restoration procedure, and results are presented to the user through friendly user interfaces. This simulator can be used to study the system restoration procedure and to investigate possible future installations of black-start units and their capacities.

Key Words: power system blackout, restoration strategy, graph theory

I. Introduction

Even though current bulk power systems provide a reliable supply of electric power, transitions into a restorative state are not rare events. It has been reported that, in the United States, 48 large outage events occurred from 1979 to 1983. In about 40% of the events reported, there existed dispatch difficulties (Adibi *et al.*, 1987a, 1987b; Adibi and Scheurer, 1988; Adibi, 1993; Adibi and Fink, 1993; Kafka *et al.*, 1982; Cooper and Adibi, 1992; Teo, 1992). The Taiwan Power Company (Taipower) experienced an island wide blackout in 1976, and since then reviews of system operation procedure for handling blackout situation have been conducted at frequent intervals by the engineers of various departments of Taipower. Because of the fast load growth and the continuous extension of the system, the possibility of major outage has greatly increased. Due to the installation of many new capacious generation units, extra high voltage transmission lines and underground cables which require longer start-up times and have large charging effects, dispatchers are not able to effectively handle the system situation after the occurrence of a system wide outage.

In order to assist power system dispatchers following a complete collapse of the power system, many electric companies have developed system restoration schemes to meet their particular needs during a blackout period. Most of these schemes contain general guidelines which serve to define the required restoration plans. However, these restoration guidelines do not take into account many of the possible system structures and/or operating conditions that can be encountered during the restoration process. Review of past system operation experiences has revealed operation difficulties due to changes in the system configuration, the occurrence of unforeseen circumstances and outdated dispatch strategies.

After a system wide outage, the restoration process is filled with uncertainty and complexity. Therefore, it is difficult to study the problem using a single mathematical formulation. The major problems associated with power system restoration are as follows (Adibi *et al.*, 1987a, 1987b; Adibi, 1993; Adibi and Fink, 1993; Simburger and Hubert, 1981):

(1) detection of fault location,
(2) identifying the energizing path,
(3) generation and load balancing,
(4) reactive power balancing,
(5) low frequency and overvoltage control,
(6) switching transients control, and
(7) cold load pickup.

The power system control problem can be formulated in general terms by a set of non-linear algebraic equations and a set of non-linear differential equations as follows (Nadira *et al.*, 1992):

Objective function:

$$\min_{x,u,d,c} F(x, u, d, c) \tag{1}$$

Subject to:

$$g(x, u, d, c, t)=0 \; .$$

$$\dot{x}=f(x, u, d, c, t)$$

where

x=set of state variables
u=set of manipulated or control variables
d=set of disturbances or uncertainties
c=the system configuration or topology

All the variables (x, u, d, and c) are functions of time, t.

In the system restoration problem, the objective function may be one of three separate types: (1) to minimize the restoration time, (2) to maximize the load served at all times, and (3) to minimize the number and the magnitude of the control actions to be taken. These three objectives are typically in conflict. In general, we can only use the formulation to characterize a part of the control problem in a small time period. Due to the fact that the power system restoration control problem is non-linear and uncertain, a single formulation and its solution may not be able to complete the restoration task. Therefore, the restoration process can be described as a multi-source, multi-objective, multi-variable constrained search problem. In order to solve this problem, a stage restoration approach would be useful. The restoration process can be divided into many stages (subproblems). Each stage has a unique initial condition, objective function, and operation strategy. It is necessary to manipulate these stages sequentially until all the stages are completed (Shimakura, 1992; Gaing *et al.*, 1996). Each stage can be characterized and solved using heuristic knowledge rules or a mathematical model (e.g. Eq. (1)).

In order to provide assistance to power system dispatchers following a complete collapse of a power system and to increase the ability to process these emergency events, a research project was conducted to develop a computer simulator that incorporates graphic interfaces and knowledge based techniques. Through an interactive and friendly graphic interface, the prototype system can suggest guidelines for dispatchers to help them restore the system. Practical operation rules obtained from dispatcher operation documents (*Taipower System Operations Manual*) are included in this simulator to provide a feasible and practical procedure for system restoration. A network analytical algorithm and graph theory are used to analyze transient and steady state system behavior and to conceive a restoration plan. The structure and functions of the simulator and the associated development procedures are described in the following sections.

II. Power System Restoration Procedure

Restoration procedures are developed based on certain operating principles, past experience, and the characteristics of power plants as well as other apparatuses. In order to handle a blackout situation, Taipower has developed system restoration rules which have been accumulated from operational experience over a period of several decades. Despite the complexity of the restoration procedure, the procedure can be broken down into a sequence of tasks. The tasks and issues addressed in this package are as follows (Taipower Company, 1991):

(1) Identify the status of the collapsed system, components and equipments. After a system wide outage, the system should be divided into three areas: North, Central and South areas. Restart of each area should be conducted independently. Breakers should be changed to the pre-specified status. All sources of reactive power should be removed from the system, and automatic load shedding should be deactivated. Circuit breakers on the primary side of the transformers should be closed.

(2) Restart black-start units, and supply station service to power plants and substations. Hydro and gas turbine units are used to provide cranking power for thermal units.

(3) Coordinate power plant start-up timings with load pick-ups to bring generators to their stable minimum levels.

(4) Maintain reactive power balance by: (i) energizing sections of transmission lines with acceptable transient and sustained overvoltages; (ii) initially energizing only one circuit of double circuit transmission lines; and (iii) operating generations under-excited to the extent that stability consideration is allowed. Restoration of the 161 Kv system should be completed before the 345 Kv system.

(5) Pick up loads in large increments without risk of excessive frequency decline and system instability.
(6) Maintain system voltages within plus and minus 5% by: (i) setting generator voltages at the low end of the allowable range during the early stage of restoration; and (ii) adjusting transformer taps to appropriate positions.
(7) Firm up the transmission system by interconnecting restored subsystems. Reintegrate the skeleton of the entire power system with consideration given to requisite time-consuming switching operations. Reduce the standing phase angles when closing loops to firm up transmission paths. Area synchronizations should be conducted only at substations with synchronization equipment.

These procedures can be roughly classified into four stages based on theory features. Fig. 1 shows the divided stages of the restoration process. The first stage identifies the network status. The tasks listed under 1 of the above mentioned issues are taken care of in the first stage. In the second stage, the shortest reenergetic path between any two split groups of plants and substations is found. In this stage, tasks 2, 3, 4, and 7 are performed. In the third stage, expansion of the live area of the system, and tasks 3, 4, and 6 are carried out. In the fourth stage, restoration of load centers service is completed, and tasks 3, 5 and 6 are executed.

III. System Implementation

The work and problem formulation involved in each stage of Fig. 1 is elaborated on in the following:

1. Restoration Strategies Module

Stage 1: The overall Taipower system is represented by a graphic network. Generation stations and substations are assumed to be nodes and transmission lines to be branches. By acquiring the breaker (ON/OFF) status from the SCADA system and by making phone calls to major power plants and substations, a connection analysis algorithm can be used to identify the network status and configuration (Bondy and Murty, 1988).

Stage 2: During a system wide outage, the system is divided into three areas: North, Central and South areas. Restarting of each area is conducted independently only if there is sufficient black-start capability to provide cranking power to the thermal units in each area. The criteria for judging whether the cranking power is sufficient or not is expressed as

$$P_{g,\text{blk\_start}} \geq P_{k,\text{crank\_pwr}}$$

$$P^{\min}_{g,\text{blk\_start}} \leq P_{g,\text{blk\_start}} \leq P^{\max}_{g,\text{blk\_start}}, \qquad (2)$$

where

$P_{k,\text{crank\_pwr}}$ is the cranking power requirement of generation station k, and
$P_{g,\text{blk\_start}}$ is the generation capacity of black-start unit g.

This stage has also the responsibility of searching for the best reenergetic paths from power plants to substations or between any two split subsystems. The shortest path algorithm is used to search for the best path (Bondy and Murty, 1988). Due to the light load condition, the path with the lowest shunt charging quantity is determined in order to avoid overvoltage during the early restorative stage. The criteria for deciding on the reenergetic path between any two nodes i, j is formulated as

$$\min_{k} \sum_{i}^{j} C_{k,i}, \qquad (3)$$

subject to

$$C_{k,i} \leq C_{1\_\text{critical}}$$

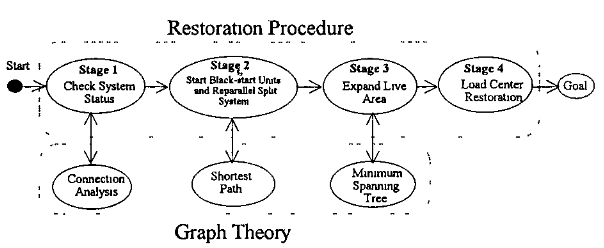

Fig. 1. Restoration strategies.

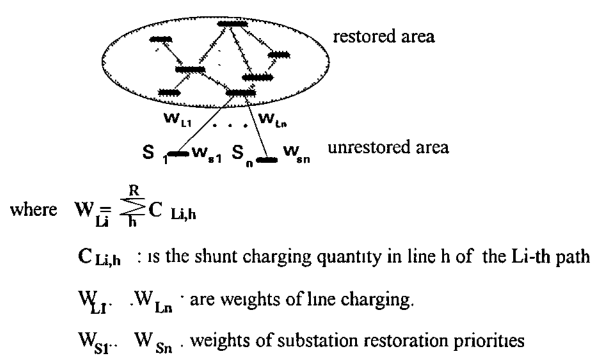

Fig. 2. Description of the load restoration priority.

$$\sum_{i}^{j} C_{k,i} \le C_{p\_critical},$$

where

$C_{k,i}$ is the shunt charging quantity in line i at the kth path,

$C_{l\_critical}$ is the tolerance of individual line charging, which is set to 0.2 pu, and

$C_{p\_critical}$ is the total tolerance of line charging, which is set to 0.25 pu.

Stage 3: The load center priority and shunt charging quantity of transmission lines are used to sort the sequence of steps in load center restoration and transmission line reenergization. Restoration of important loads based on the generation capacities of units is conducted to maintain power balance. The minimum spanning tree algorithm is used to achieve this goal (Bondy and Murty, 1988). The decision on the load center restoration sequence can be determined by using Eq. (4). The shunt charging of transmission lines is represented by using weights between two nodes.

$$\min_{i} W_{L,i} + W_{S,i} \tag{4}$$

subject to constraints in Eq. (3),

where

$W_{L,i}$ is the weight of line charging in line i, and

$W_{S,i}$ is the weight of the restoration priorities of substation i.

Stage 4: This stage is mainly needed to decide on the quantity of the restorative load based on the available generation capacity units and the load center restoration order from stage 3. There are two situations which need to be considered in this stage:

(1) In the early stage of system restoration, the generators are started up one by one until each generator reaches full load. Generators often supply power to load centers in sequence. Based on a generator's min. and max. capabilities, and its ramping limit, the generation increment at a certain time interval can be determined and distributed to load centers based on their priority.

(2) When many units have been restored to provide power to load centers simultaneously, Eq. (5) is used to decide on the total power increase provided by available units, that is, how much load can be restored (Glover *et al.*, 1994), and Eq. (6) is used to decide how much power is supplied by each individual unit:

$$\Delta p_T = \Delta p_{ref} - \beta \Delta f, \ \beta = 1/R_1 + 1/R_2 + \ldots + 1/R_N \tag{5}$$

$$\Delta p_i = -\frac{1}{R_i}\Delta f, \ i = 1, \ldots, N, \tag{6}$$

where

Δp_T is the total change in turbine mechanical powers (MW),

Δp_i is the increase in power output of available unit i,

β is the area frequency response characteristic (MW/Hz),

Δp_{ref} is the total change in the reference power setting within the area (MW), generally, $\Delta p_{ref}=0$,

Δf is the change in frequency within the area (Hz), $\Delta f_{min} < \Delta f < \Delta f_{max}$,

R_i is the regulation constant of the ith unit within the area (Hz/MW). A standard regulation constant is R=0.05 pu.

According to the Taipower operation guidelines, a change in frequency is allowed to be within ± 5%; hence, the change in frequency is set to at Δf_{max}=0.5 Hz, Δf_{min}=−0.5 Hz. The operator can observe the change in the frequency of the system and adjust the regulation constant R of the unit to decide how much load can be restored without causing the system to become unstable.

In the above mentioned stages, both load flow and switching transient analytical programs are executed to validate the security of the system at every restoration step.

2. Analytical Program Module

A power flow program is used to validate the real and reactive power balance and to avoid sustained overvoltages and thermal overloads. The following constraints are respected.

(1) Limits of generation capacities

$$\sum_{i}^{N_L} P_{L,i} \le \sum_{j}^{N_g} P_{g,j}, \tag{7}$$

where

$$P_{g,j}^{\min} \le P_{g,j} \le P_{g,j}^{\max}$$

and

$P_{L,i}$ is the active power demand at bus i, and

$P_{g,j}$ is the active power generation at bus j.

(2) Limits of bus voltages:

$$V_i^{\min} \le V_i \le V_i^{\max}, \quad (8)$$

where

V_i is the bus voltage at bus i.

(3) Limits of line flows:

$$P_k \le P_k^{\max} \text{ and } Q_k \le Q_k^{\max}, \quad (9)$$

where

P_k is the active power flow on line k, and
Q_k is the reactive power flow on line k.

A switching transient program is used to determine transient voltages in energizing high voltage transmission lines. Though there are only two analytical programs contained in the simulator, the environment permits the addition of other simulation programs.

The system was implemented on a SUN Sparc 10 workstation with 32 MB main memory and a 2 giga byte hard disk. The main software requirements of the present system are (1) the general purpose graphics software AutoCAD, (2) analytical software, and (3) a restoration assistant program. Figure 3 shows the software sub-modules of the environment.

IV. Case Study

The graphics module allows users to interface with analytical programs and to display simulation results as well as the following data:

(1) summary tables and a system diagram of each subsystem as well as detailed substation one-line diagram;
(2) physical characteristics data such as parameters and ratings;
(3) operational characteristics data, such as the system load, generation, and operating reserve in the system.

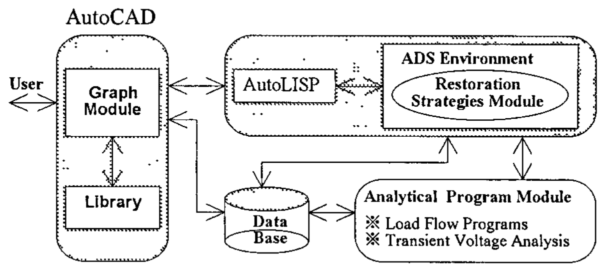

Fig. 3. Software sub-modules

The restoration assistant program can be activated by keying in the "restore" command on the command window or by choosing the item in the pull-down menu on the screen. With the graphics environment, the user can visualize the energization process at its various stages. It also provides dispatchers with the sequence of switching operations required to energize the system.

The Taipower system was used to validate satisfaction of the system requirements. Table 1 shows a summary of the generation and transmission facilities of the current Taipower system. In the initial stage of the restoration procedure, the system is divided into three areas: North, Central and South areas. Restarting of each area is conducted independently, and the areas are then tied together at the sonsu and wufan substations. Each area has black-start capability to provide power to thermal units, as Table 2 shows.

Due to space limitations, we will show only the system restoration test results for the South area network of the Taipower system. The area has one nuclear power plant, two thermal power plants, four hydro plants, 28 (161 Kv and 345 Kv) substations, and 49 transmission lines. There are three power plants with black-start units, which are <u>dakwan-1(hydro)</u>, <u>dgikon(hydro)</u>, and <u>dalin(gas turbine)</u>. The total capacity of the generation units and load of the substations in this area are 6290MW and 9450MVA, respec-

Table 1. Summary of Current Generation and Transmission Facilities of the Taipower System

Generation				Substation			Transmission Line		
Type	Nuclear	thermal	hydro	Type	EHV (345Kv)	UHV (161Kv)	Type	EHV (345Kv)	UHV (161Kv)
No. of Stations	3	6	34	No. of Stations	12	78	No. of Lines	52	217
No. of Units	6	31	165	–	–	–	Length (km)	2524	4004

Table 2. Black-Start Units of the Taipower System

Area	Main Black-start Units (MW)	Need to be Reenergized Units	Reverse Units
North	smen (90MW)	shehar, linkor, senau, nuclear_1, nuclear_2	linkor diesel & gas, festwen, wulai, kwesun, lanyun, teban
Central	kwukwan (180MW), dargi (230MW)	taijong, tuoshiau	dakwan_2, chisun, tenlun, minten
South	dakwan_1 (110MW) dgikon (40MW)	dalin, sinda, nanhor, nuclear_3	zhuwun, wanda, dalin_gas

tively. Table 3 shows a summary of the generation facilities of the South area.

When the area experiences blackout, the loading factor is assumed to be about 0.6. First, the simulator suggested that the operators perform some necessary operation tasks. These include opening all end breakers of transmission lines and power capacitors in the substations, and then resetting all the breaker states in the power plants and substations according to the blackout restoration operation manual and the "*Extra High Voltage and Primary System Blackout Operation Directive Drawing*" of Taipower. Upon the completion of the reset tasks, the simulator then starts to propose a feasible restoration procedure to the operator. The suggested restoration procedure is as follows:

In Stage 1 the system split status is determined using the connection analysis algorithm. Figure 4 shows the South area system network after blackout has occurred. The yellow and green lines on the displays represent the 345Kv and 161Kv transmission lines individually that are yet to be reenergized.

Stage 2 involves starting up these black-start units and searching for the optimal reenergetic paths between black-start and thermal units so that cranking power can be provided to thermal units. When the procedure is completed, the optimal tie path between any two split subsystems is located. In Fig. 4 the right window in the display shows a suggestion to start the dakwan-1 hydro units and to then transmit power to the sinda plants. If the operator accepts the suggestion, those transmission lines to be reenergized would change color in the display. Sequentially, the digkon hydro unit will start up successfully. In order to balance power between generation and load, it suggests restoring a part of the puli substation load. When the dalin black-start units start running. It not only provides power to other thermal units, but also provides the kaohsiung substation with a part of its vital load. All the status information about transmission lines and restored loads is displayed to the operator. In order to improve system stability, the resynchronization task must be completed. The simulator suggests the optimal tie paths from kaohsiung to serwu to gangsun and to lonchin, and these messages are shown in Fig. 5.

The goal of Stage 3 is to expand the love area of the system. The minimum spanning tree algorithm is used to achieve this goal. The simulator suggests a sequence for load restoration which is suwei, wanda, sunmin, jimin, siin, tainan, annan, rensu, bankong, ianhan, yunlin, sianban, tazon, jonkaug, danwu, taidon, hwualan. The sequence for reenergizing transmission lines is wujea→suwei, puli→wanda, kaohsiung →sunmin, jiai→jimin, sunsan→siin, lonchin →tainan, sunsan→annan, gangsun→rensu, jimin→ bankong, annan→ianhan, jimin→yulin, annan→ sianban, nankong→tazon, nankong→jonkaug, fogang →danwu, danwu→taidon, taidon→hwualan. Figure 6 shows one of the message windows in this stage.

In Stage 4, the total amount of load increment every time must be lower than 5% of the total current generation in order to avoid any instability in the system. Figure 7 shows the network diagram after the restoration procedure is completed. Twenty-eight substations and 35 transmission lines are restored. At this time, the total amount of generation is 5699+j1869.2MVA, and the total load is 5670+j1859.7MVA. Some 345Kv transmission lines have not yet been reenergized because the shunt charging current is much larger than 161Kv during the early stages of restoration. The amount of restoration time depends on the start up times of the thermal and nuclear units. Therefore, 3-4 hours could be required to complete the

Table 3. Summary of the Generation Facilities in the Southern Area

Unit Name	Type	Capacity (MW)
nuclear_3	nuclear	1950
sinda	thermal (coal)	2100
dalin	thermal (oil, coal, gas)	1950
nuclear_3_gas	thermal (gas)	120
dakwan_1	hydro	100
dgikon	hydro	40
wanda	hydro	30

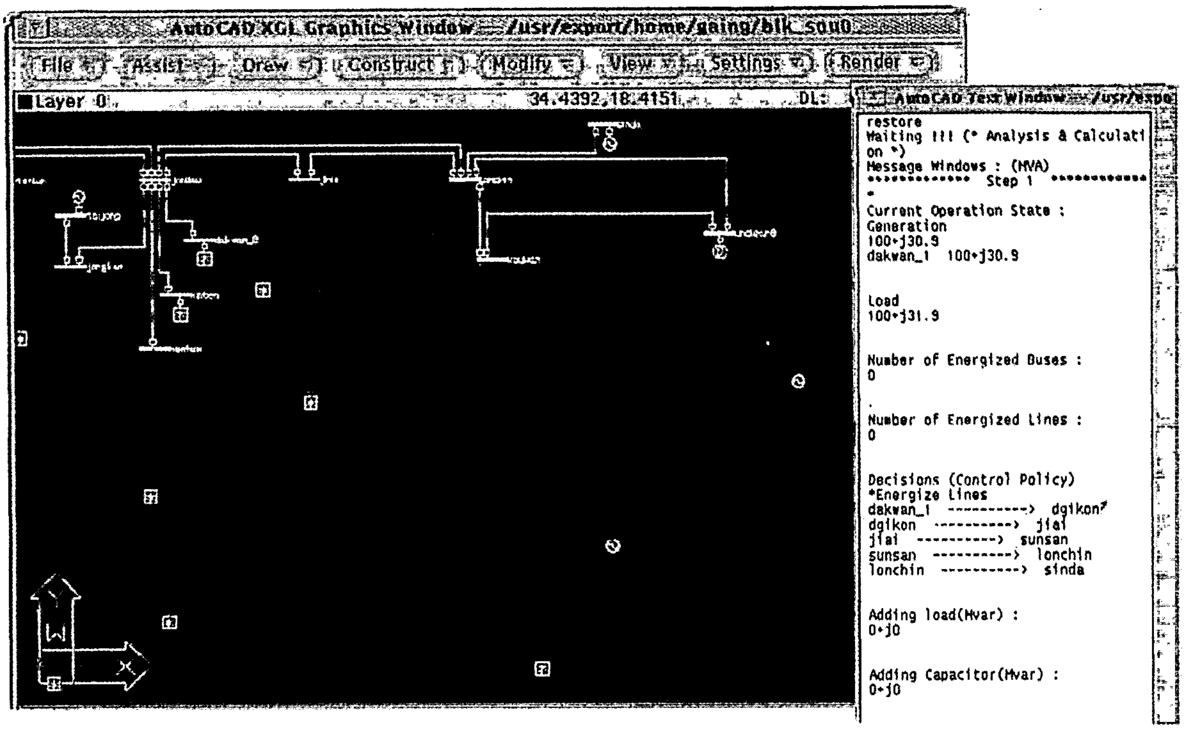

Fig. 4. The suthern area network configuration; at right is the restoration operation message window.

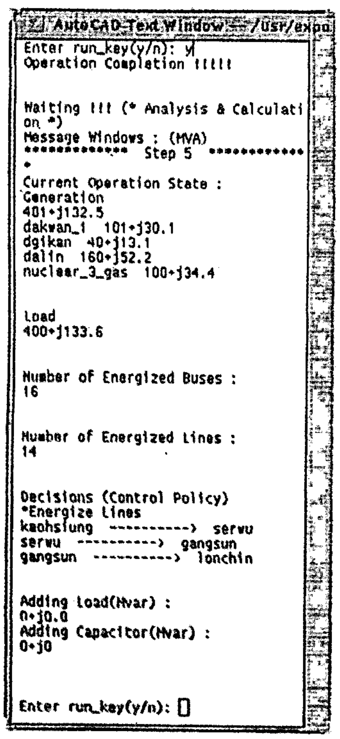

Fig. 5. The window shows a rresychronous message between two subsystems.

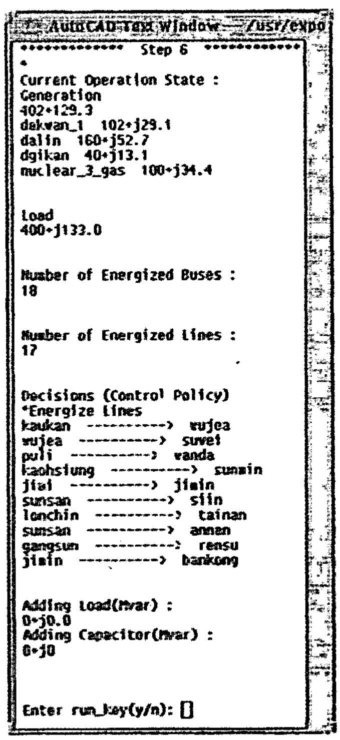

Fig. 6. The window shows one operation message during system basic network building.

restoration tasks in the area.

The "*Taipower System Operation Manual*" and "*Extra High Voltage and Primary System Blackout Operation Directive Drawing*" are currently used by

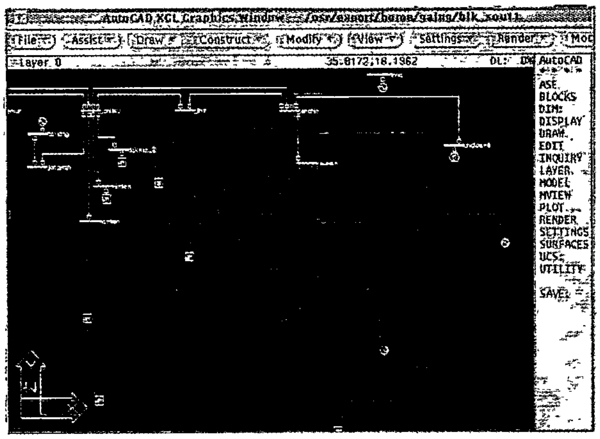

Fig. 7. System configuration when the restoration operation is completed.

Taipower to handle for handling blackout events. Compared to the tools currently used by Taipower, the proposed simulator seems to have prominent advantages in terms of flexibility and user friendliness. The restoration procedure could adapt to changing conditions of the system and guide dispatchers as they to perform system restoration in a more efficient manner.

V. Conclusion

In this paper, we have presented a prototype system for providing aids to the dispatcher for conducting power system restoration and dispatcher training. The simulator utilizes a multi-stage approach to overcome many of the power system restoration problems. The features of the prototype simulator are: (1) it can propose the optimal step by step restoration procedure based on the current system status; (2) in order to reduce the risk level or failure probability, some security validation measures are performed; (3) it provides a friendly and lively graphic user interface to show pertinent system data and the restoration process.

Acknowledgment

The financial support provided by the National Science Council of the Republic of China under the Grant NSC 84-2213-E-110-029 is gratefully acknowledged. The first two authors would like to thank the system operators of the Taipower Central Dispatching Office for their time and support.

References

Adibi, M. M. (1993) Special consideration in power system restoration-the second working group report. *IEEE Trans. on Power Aparatus and Systems*, **8**(1), 191-197.

Adibi, M. M. and D. Scheurer (1988) System operations challenges: issues and problems in power system restoration. *IEEE Trans. on Power Systems*, **3**(1), 123-134.

Adibi, M. M. and L. H. Fink (1993) Power system restoration planning. *IEEE Trans. on Power Aparatus and Systems*, **9**(1), 22-28.

Adibi, M. M., P. Clelland, L. Fink, H. Happ, R. Kafka, J. Raine, D. Scheurer, and F. Trefny (1987a) Power system restoration-a task force report. *IEEE Trans. on Power Systems*, **2**(2), 271-277

Adibi, M. M., J. N. Borkoski, and R. J. Kafka (1987b) Power system restoration-the second task force report. *IEEE Trans. on Power Systems*, **2**(4), 927-933.

Bondy, J. A. and U S. R Murty (1988) *Graph Theory with Application*. North-Holland, New York, NY, U.S.A.

Cooper, M. E. and M. M. Adibi (1992) Bulk power system restoration training techniques. *IEEE Trans. on Power Aparatus and Systems*, **9**(1), 15-21.

Glover, J. D., and M. Sarma (1994) *Power System Analysis and Design with Personal Computer Applications*, Chapter 11, 2nd Ed PWS Publishing Company, Boston, MA, U.S.A.

Gaing, Z. L., C. N Lu, B. S. Chang, and C. L. Cheng (1996) An object-oriented approach for implementing power system restoration package. *IEEE Trans. on Power Systems*, **11**(1), 483-489.

Kafka, R. J., D. R. Penders, S. H. Bouchey, and M. M. Adibi (1982) Role of interactive and control computers in the development of a system restoration plan. *IEEE Trans. on Power Aparatus and Systems*, **101**(1), 43-52.

Liu, C. C., S. J. Lee, and S. S. Venkata (1988) An expert system operational aid for restoration and loss reduction of distribution systems. *IEEE Trans. on Power Systems*, **3**(2), 619-626.

Nadira, R., T. E. D Liacco, and K. A. Loparo (1992) A hierarchical interactive approach to electric power system restoration. *IEEE Trans. on Power Systems*, **7**(3), 1123-1131.

Shimakura, K. (1992) A knowledge-based method for making restoration plan of bulk power system. *IEEE Trans. on Power System*, **7**(2), 914-920

Simburger, E. J. and F. J. Hubert (1981) Low voltage bulk power system restoration simulation. *IEEE Trans. on Power Apparatus and System*, **100**(11), 4479-4484.

Taipower Company (1991) *Power System Operation Manual*. Taipower System Operations Department, Taipei, R.O.C.

Teo, C. Y. (1992) A computer aided system to automate the restoration of electrical power supply. *Electric Power Systems Research*, **24**, 119-125.

Wu, F. F. and A. Monticelli (1988) Analytical tools for power system restoration - conceptual design. *IEEE Trans. on Power Systems*, **3**(1), 10-16.

全停電復電調度訓練器之研發

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摘　要

由於對電力品質要求的不斷提昇，電力公司無不致力於提高供電系統的可靠度與穩定性。然而基於許多大停電事故造成巨額經濟損失及廣大影響層面之先例，因此合適的系統復電調度策略正積極的被研究，以期在輸電系統遭受到重大故障後，能夠迅速恢復系統供電能力。本文就提出了運用階段性復電方式、結合啟發式法則與改良的圖形理論演算法、多種電力系統分析軟體，並配合台電電力調度規則，以台電系統爲基礎，而發展出來的一套具友善操作介面的電腦輔助電力系統全停電復電操作訓練器。此模擬器不僅可製訂出合理的系統復電操作程序，並可用於探討未來系統裝置全黑啟動機組之合適位置與容量。