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A KNOWLEDGE-BASED APPROACH TO IMPROVING OPTIMIZATION TECHNIQUES IN SYSTEM PLANNING

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ABSTRACT

The paper presents a knowledge-based (KB) approach to improve mathematical programming techniques used in the system planning environment. The KB system assists in selecting appropriate optimization algorithms, objective functions, constraints and parameters. The scheme is implemented by integrating symbolic computation of rules derived from operator and planner's experience and is used for generalized optimization packages.

The KB optimization software package is capable of improving the overall planning process which includes correction of given violations. The method has been demonstrated on a large-scale power system discussed in the paper.

Keywords: System Optimization, System Planning, Expert System, Power System, Security Analysis, Optimal Power Flow.

INTRODUCTION

The planning of large-scale system requires the use of optimization techniques and software programs. Many of the optimization algorithms developed to solve planning problems include recursive quadratic programming, the cost function method, the feasible direction method, etc. All of these methods have certain common calculation during each iteration. They all need appropriate selection of objective functions, constraints, prioritization of contingencies and some mechanism to enforce global convergence.

The implementation of these algorithms calls for human judgment to efficiently use the software package dedicated for optimization tools available. To achieve an improvement over traditionally used planning processes, the technique uses a staged approach to planning and employs a knowledge-based support to assure optimal performance of available optimization packages.

The paper is organized into four major sections. Section one deals with the concept of knowledge-based hierarchical optimization (KBHO). Section two deals with application of the knowledge-based system to security assessment in planning. The third section implements the expert system for power systems problem,while section four gives a summary of results and concluding remarks.

THE CONCEPT OF KNOWLEDGE-BASED HIERARCHICAL OPTIMIZATION

The knowledge-based hierarchical optimization (KBHO) is conceived for improving system-wide planning problems for a typical large-scale system. The generalized optimization problem is formulated below. The stages of planning process and the rules of the expert system are identified.

Formulation of Optimization Problem

The optimization problem of large-scale systems can be formulated as given by (Toint, edited by Osiabacz, Clarendon Press, 1988).

$$\min \ f(x) \tag{1}$$

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subject to

$$l \le X \le u, \quad (2)$$

$$AX \le b, \quad (3)$$

$$CX \le 0, \quad (4)$$

where $f: R^n \rightarrow R$ is the objective function, l, $u \in R^n$ are the lower and upper bounds on the variables, A is an m x n matrix, $b \in R^m$ and $C: R^n \rightarrow R^m$ represents the non-linear constraints.

Stages of Planning Process

Three different stages are included in the planning process. Figure [1] displays the basic structure and the interactions between the various stages.

(a) System Modeling

A modeling description of the planning problem is given by the planner. This involves the selection of available models and preparation of input data. KB support is provided at this stage to improve the data and to select the appropriate optimization model.

(b) System Planning

A schedule of the plan needed to achieve a specified scenario is given, while at the same time the validity of the plan is checked. If the plan fails, or is unavailable, we return to stage (a) to modify or change the model description.

(c) System Simulation

The selected plan and optimization model is simulated until the planner is satisfied with the generated plan. If the plan turns out to be infeasible, the proposed KB checks the algorithm for convergence and suggests remedial action to improve the plan or adjust the parameters.

The solution of the optimization problem stated in equations (1) through (4) is implemented to guarantee an optimum solution

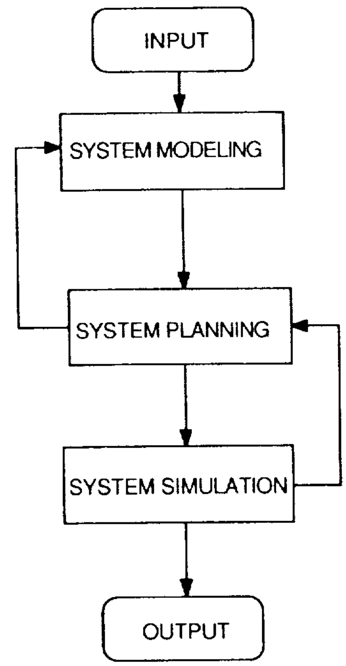

FIGURE 1: A BASIC PLANNING PROCESS

by optimizing the stages discussed above. The proposed expert system implements the planning process by performing staged sequential performance of decision-making process. It couples knowledge-based components with numerical computation programs. By using a hierarchically structured data transfer, storage and updating of data and knowledge is improved. Thus, the overall planning scheme is enhanced. The four major levels of the suggested KBHO scheme is described below.

Level I: Identification of Hierarchical and Multi-level Decision-Making Process

This level identifies the numerical computation process at a decision-making (DM) subprocess. The options considered are appropriate modeling, algorithms needed for given tasks, selection of constraints and objective functions, evaluation of parameters and convergence criteria.

Level II: Knowledge-Based and Optimal Selection of the Options

This level employs the KB support to select the options constructed in the upper level. This is accomplished by using deductive reasoning and flexible man-machine interaction at lower levels. The selection is based on fully integrated information and available optimization techniques.

Level III: Implementation of Mathematical Programming Problem

This level solves the proposed optimization problem by using the appropriate mathematical programming method. Several methods are available and selection according to task is done by employing knowledge-based support in IV.

Level IV: Implementation of KB Synthesis

This level employs the expert system at the top level of the planning process. It guarantees a system-wide optimum by ensuring staged optimization. It assists in the coupling of numeric and symbolic computation program modules, and also guarantees man-machine interaction between the user and the KB planning process.

EXAMPLE OF SYSTEM PLANNING PROBLEM

The optimal power flow (OPF) has been successfully employed in the electric power industry to determine the optimum allocation and scheduling of power systems. Optimal power flow has also been used for security assessment due to the impact of loss of line or unit contingency. (Alsac et al., IEEE, 1974) have developed an off-line optimization scheme based on nonlinear optimization to determine specified objectives and constraints.

The proposed KBHO is designed for on-line use and is capable of selecting different objective functions and associated constraints. The evaluation of the impact of contingencies and the selection of optimum strategy have been improved.

Optimal Power Flow Problem

In general, the optimal power flow problem in normal operation of power system is described mathematically as follows:

$$\min F(x, u) \tag{5}$$

subject to

$$g(x, u, p) = 0 \tag{6}$$

$$h(x, u, p) \leq 0 \tag{7}$$

where X is the state variable vector for voltage magnitudes and angles, u is the controllable variable vector for generation outputs and transformer taps, etc and P is the uncontrollable variable vector for admittances in networks. The function F(x, u) is the objective function representing operation costs, power loss, voltage deviation, etc. Equation (6) denotes equality constraints and equation (7) represents inequality constraints.

Options of Objective Functions and Constraints

Several options of objective functions and associated constraints are developed in quadratic form as shown in [Momoh, SMC 1989].

The objective function is given as

$$F(x) = 1/2X^T RX + a^TX \tag{8}$$

for loss, cost, voltage deviation and their combinations. Their associated constraints are defined as

$$F_i(x) = 1/2X^T H_iX + b^TX = K_i \tag{9}$$

where $K_{i1} \leq K_i \leq K_{i2}$; $i = 1, 2, \ldots m$.
and K_{i2} and K_{i1} are upper and lower limits constraints.

Details of the objective functions and constraints are given in Tables 1 and 2. Various parameters and variables of the objective functions and the constraints are defined in Tables 3, 4 and 5. Table 6 gives a summary of the various possible combinations of the constraints for each objective function.

Objective Functions	FORMULATION	DESCRIPTIONS
OF_1	$\frac{1}{2}x^T D x - DV^T x$	Voltage Deviation Minimization
OF_2	$\frac{1}{2}P_{KE}^T R_C P + a_C^T P_{KE}$	Cost Minimization
OF_3	$\frac{1}{2}P_{KE}^T R_L P_{KE} + a_L^T P_{KE}$	Loss Minimization
OF_4	$W_1 OF_2 + W_2 OF_3$	Production Cost & Loss Min.
OF_5	$W_1 OF_1 + W_2 OF_2 + W_2 OF_3$	Voltage + Current + Loss

TABLE 1: SUMMARY OF DESCRIPTIONS OF OBJECTIVE FUNCTIONS

Constraints	FORMULATION	DESCRIPTIONS
Const. 1	$V_{KE\,min}^2 \leq \lvert V_{KE}\rvert^2 = \frac{1}{2}x^T H_{vx} + b_v^T x \leq V_{KE\,max}^2$	Voltage Constraints
Const. 2	$P_{KE\,min} \leq P_{KE} = \frac{1}{2}x^T H_{2K-1}x + b_p^T x \leq P_{KE\,max}$	Real Power Constraints for Generator
Const. 3	$Q_{KE\,min} \leq Q_{KE} = \frac{1}{2}x^T H_{2K}x + b_q^T x \leq Q_{KE\,max}$	Reactive Power Constraints for Generator
Const. 4	$P_{KD\,min} \leq P_{KD} = \frac{1}{2}x^T H_{2K+1}x + b_D^T x \leq P_{KD\,max}$	Real Load Power Constraints
Const. 5	$P_{DK\,min} \leq P_{DK} = \sum_{i=1}^{g} (1-B_i)P_i - \sum_{i=1}^{g}\sum_{j=1}^{g} P_i B_{ij} P_j \leq P_{DK\,max}$	Demand Constraints
Const. 6	$\lvert I_{ij}\rvert^2_{min} \leq \lvert I_{ij}\rvert = \frac{1}{2}x^T H_I x \leq \lvert I_{ij}\rvert_{max}$	Current Constraints

TABLE 2: Summary of Constraints

Variables	DESCRIPTION
x	Voltage vector, $2n \times 1$, real and imaginary part of voltage
V	Expected voltage value vector, $2n \times 1$
P_{KE}	Real Power of Generator, $g \times 1$
n	Bus number of of a given system.
g	Generator number of a given system.

TABLE 3: Objective Function Variable Description

Variables	DESCRIPTION
D	Weight Coeffieciency Matrix, diagonal matrix with positive elements
R_C	$R_C = \mathrm{Diag}[a_1, a_2, \ldots, a_g]$, a_i is the cost efficiency of the generator
a_C	$a_C = [b_1, b_2, \ldots, b_g]$, b_i is the cost efficiency of the generator
R_L	$R_L = [B_{ij}]$ is the matrix of Loss coefficiency with $B_{ji} = B$
a_L	$a_L = [B_1, B_2, \ldots, B_g]$, B_i is the Loss coefficiency

TABLE 4: Objective Function Parameter Description

Variables	DESCRIPTION
H_v	All elements equal to zero but $(2k-1)^{th}$ and $2K^{th}$ elements equal to 2
H_I	Has at most eight non-zero elements $H_I(2i-1, 2k-1) = H_I(2j-1, 2j-1) = H_I(2i, 2i) = H_I(2j, 2j) = 2(G_{ij}^2 + B_{ij}^2)$ $H_I(2i-1, 2j-1) = H_I(2j-1, 2i-1) = H_I(2i, 2j) = H_I(2i, 2j) = -2(G_{ij}^2 + B_{ij}^2)$
H_{2k-1}	$\begin{bmatrix} 0 & \begin{matrix} B_{k1} & G_{k1} \\ -G_{k1} & B_{k1} \end{matrix} & 0 \\ & \vdots & \\ B_{k1}\ -G_{k1} \cdots & 2B_{kk}\ \ 0 & \cdots B_{kn}\ -G_{kn} \\ G_{k1}\ -B_{k1} \cdots & 0\ \ 2B_{kk} & \cdots -B_{kn}\ G_{kn} \\ & \vdots & \\ 0 & \begin{matrix} B_{kn} & G_{kn} \\ -G_{kn} & B_{kn} \end{matrix} & 0 \end{bmatrix}$
H_{2k}	$\begin{bmatrix} 0 & \begin{matrix} G_{k1} & -B_{k1} \\ B_{k1} & G_{k1} \end{matrix} & 0 \\ & \vdots & \\ G_{k1}\ B_{k1} \cdots & 2G_{kk}\ \ 0 & \cdots G_{kn}\ B_{kn} \\ -B_{k1}\ G_{k1} \cdots & 0\ \ 2G_{kn} & \cdots -B_{kn}\ G_{kn} \\ & \vdots & \\ 0 & \begin{matrix} G_{kn} & -B_{kn} \\ B_{kn} & G_{kn} \end{matrix} & 0 \end{bmatrix}$
b_v, b_p, b_g, b_D	Linear term coefficiency, depend on the system
B_i	See objective function parameter description
B_{ij}	See objective function parameter description

TABLE 5: Constraint Parameter Description

Objective Function	Constraints			
OF_1	Constraint 1	Constraint 2	Constraint 3	Constraint 4
OF_2	Constraint 1	Constraint 2	Constraint 3	Constraint 5
OF_3	Constraint 1	Constraint 2	Constraint 3	Constraint 5
OF_4	Constraint 1	Constraint 2	Constraint 4	Constraint 6
OF_5	Constraint 1	Constraint 2	Constraint 3	Constraint 5

TABLE 6: SUMMARY OF OBJECTIVE FUNCTIONS AND CONSTRAINTS

Statement of Static Security Assessment Problem

The static security assessment (SSA) problem is concerned with answering the folowing question: How should the power system be operated so that failures do not cause problems? In answering this question successfully, it is important that operators know which equipment outages will cause flows or voltages to fall outside limits so that they can take appropriate measures in dealing with the harmful outages in order to maintain the system operation within safe limits.

The OPF-based static security assessment problem can be described as the performance of the following staged tasks (Thomas, EPRI, 1988) in Figure 2:

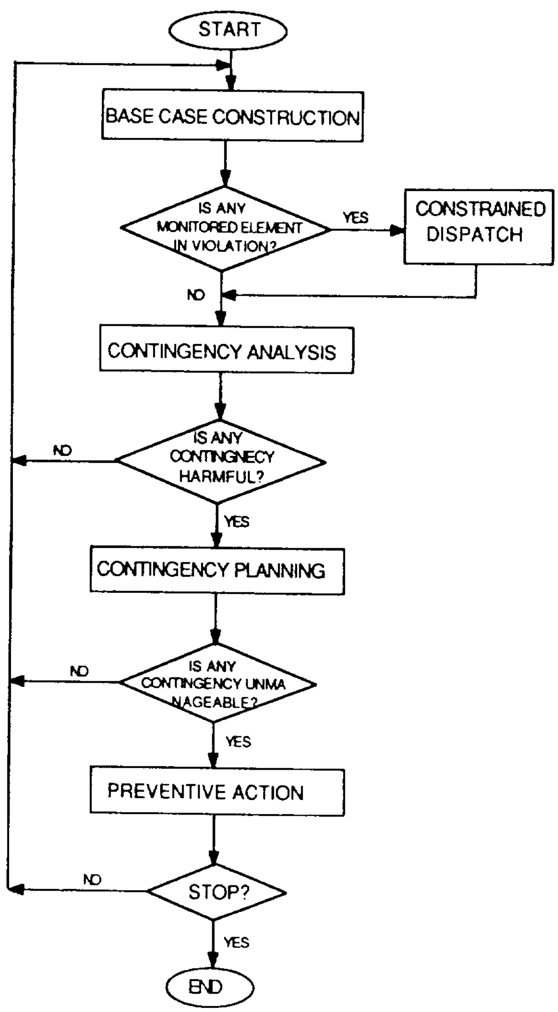

FIGURE 2: A FLOWCHART OF SSA PROCESS

1. Base Case Construction

   The goal of this module is to obtain the base case of the power flows and bus voltages in the existing system configuration for further analysis.

2. Constrained Dispatch

   The goal of this module is to call the OPF-based corrective scheme of power system operation to correct the violations from the base case.

3. Contingency Analysis

   The goal of this module is to determine harmful contingencies for further planning. It also eliminates harmless contingencies from further consideration

4. Contingency Planning

   The goal of this module is to determine the corrective scheme that would correct the harmful contingencies. This involves solving the OPF problem. The corrective scheme is saved for operator call up should the contingency occur.

5. Preventive Action

   The goal of this module is to determine a preventive correction scheme if one or more contingencies are found to be unmanageable. It also involves solving the OPF problem.

KNOWLEDGE-BASED IMPLEMENTATION

To improve the SSA scheme shown in Figure 2, a knowledge-based approach descussed earlier is employed. The knowledge base selects which constraints and objective functions are appropriate to correct given violations. It employs KBHO methodology to characterize the planning process and combines the various subtasks by coupling numeric computation and symbolic computation. The expert system scheme is built as described in the next section of the paper.

Expert System Design

The expert system is designed to support on-line planning of the OPF-based SSA. The design consists of several knowledge bases dedicated to improving the overall algorithms used in the SSA. Some of the areas of potential improvement are discussed as follows.

1. Partition system condition of the objective power system to effectively reduce the number of contingencies to be studied.

2. Categorize contingencies into critical and noncritical types.

3. Determine appropriate weights selection to represent given violation.

4. Select performance index to best match the operational status of power system.

5. Identify masking and misranking phenomena which characterize performance index used by (Ejebe, IEEE, 1979).

6. Select objective functions and constraints which will be appropriate for a given option in the planning and execution of SSA process.

The expert system is designed in four languages (DCL, C, OPS83, and FORTRAN) and includes three procedure modules as shown in Figure 3. Module 1 consists of numerical programs which are written in FORTRAN for both the Automatic Contingency Selection (ACS) and the optimization process. The second module, which performs symbolic computation, consists of symbolic programs where the rules developed are coded in OPS83. The representative rules describing each of the knowledge bases are constructed by using a forward chaining mechanism. The third module displays the interface program modules written in DCL and C and enhances man-machine.

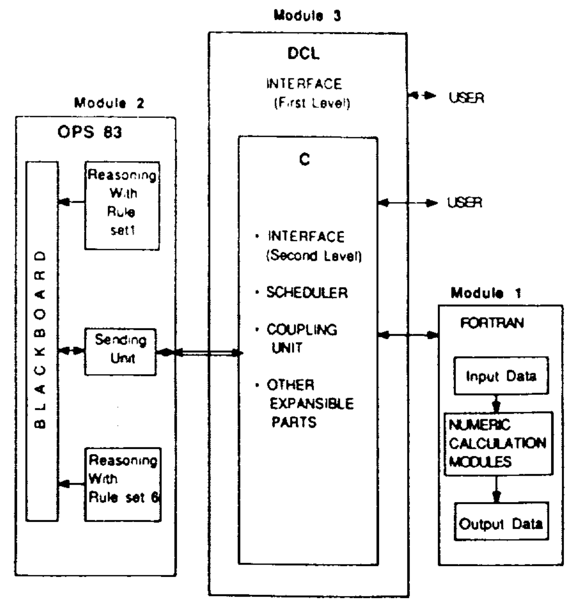

Figure 3: SYSTEM STRUCTURE OF THE EXPERT SYSTEM

TEST RESULTS

The proposed KBHO has been tested on several power systems including IEEE 14-bus, 30-bus and 118-bus test systems. The demonstration on a 14-bus system is discussed in this paper.

The objective of this study was to validate the KB support for selecting weights, misranking and masking and system partitioning while improving given performance index approach to SSA. A major loss of line for the 14-bus system causes critical contingencies leading to voltage violations. Table 6 gives the result of the ranking of contingencies in order of severity, based on the traditional performance index (PI) method (Medicherla IEEE, 1982) for voltage. The identified critical violations with and without the knowledge base (KB) are shown in Table 7. The use of KBHO leads to proper selection of appropriate weights including the identification of contingencies causing masking and misranking, thus reducing the PI lists.

Flow violations are evaluated using the PI by (Mikolinnas et al, IEEE 1981). The identified critical violations with and without KB are also shown in Table 8. The scheme is able to correctly identify appropriate weight for a given PI and at the same time reduce the effects of masking and misranking due to a given violation.

Classical Approach Using The Voltage Performance Index		Expert Aided Assisted Contingency Ranking Using The Voltage Performance Index			
Rank	PI Without KB	Masking/ Misranking Effects	Weight Selection Effects	System Partitioning	Performance Index Using KB
12*	0.5201	x	x	12*	0.1045
3*	0.0965	x	x	15*	0.0875
15*	0.0907	x	x	3	0.0700
2*	0.0373		x	2	0.0147
7	0.0350		x	7	0.0145
4	0.0158		x	4	0.0060
16	0.0146		x	14	0.0045
10	0.0114		x	10	0.0038
20	0.0075	X	x	8	0.0029
17	0.0072	X	x	5	0.0015
1	0.0047	X	x	1	0.0012
5	0.0047		x	9	0.0010
6	0.0035				
8	0.0026				
13	0.0025				
9	0.0023				
14	0.0022				
11	0.0020				
19	0.0008				
18	0.0007				

* Denotes critical contingencies

TABLE 7: IMPROVED VOLTAGE BASED PERFORMANCE INDEX (14-BUS SYSTEM)

Classical Approach Using Power Flow Performance Index		Expert System Assisted Contingency Ranking Power Flow Performance Index			
Rank	PI Without KB	Masking/ Misranking Effects	Weight Selection Effects	Rank	PI With KB
2*	4.8200	x	x	1*	4.5800
1*	4.3700	x	x	2*	3.2300
14	1.4900		x	14	2.800
6	0.1010	X	x	8	0.6070
15	0.0960	X	x	4	0.3980
9	0.0960	X	x	3	0.2800
16	0.0084	X	x	6	0.1690
17	0.0070	X	x	15	0.1650
20	0.0041	X	x	9	0.1230
13	0.0027	X	x	20	0.0535
18	0.0018	X	x	18	0.0535
19	0.0004	X	x	17	0.0164
12	-0.0292	X	x	16	0.0142
11	-0.0610	X	x	19	0.0048
8	-0.0690	X	x	13	0.0028
4	-0.1710	X	x	12	0.0231
3	-0.2500		x	11	0.0515
5	-0.4400		x	5	-0.2040
7	-0.5188		x	7	-0.3600
10	-0.9500		x	10	-0.5700

TABLE 8: IMPROVED POWER FLOW-BASED PERFORMANCE INDEX (14-BUS SYSTEM)

To test the KBHO scheme as a corrective measure for removing violations in a planning process, selection of objective functions and constraints are performed via the KB. During the effect of contingency #1 power flow violation is corrected with operating voltage limits by using the cost objective function. Other violations are similarly corrected with new operating states control and applicable objective functions identified. These results are shown in Table 9.

The KB optimization scheme is capable of selecting appropriate constraints and objectives. The scheme also guarantees convergence and improves currently used contingency screening schemes.

Contingency	Operating Range	Post Contingency Values	Corrected values	Selected Object. Function	Remarks
# 1 (Power Flow Violation)	0.000 to 0.990	1.217	0.954	Cost	Cost Objective Function was Selected to Correct Power Flow Violation
# 2 (Power Flow Violation)	0.000 to 1.080	1.225	0.982	Cost	Power Flow Constraints were Satisfied on All Circuits
# 3 (Voltage Violation)	0.925 to 1.075	0.8975	0.984	voltage	The Voltage Objective Function was Selected to Correct the Violation at bus # 10

TABLE 9: CORRECTION OF SELECTED VIOLATIONS USING CONTINGENCY-CONSTRAINED OPTIMAL POWER FLOW (14-BUS SYSTEM)

CONCLUSION

Implementation of optimization techniques in system planning involves complex interaction between human planner, numerical programs and objective system status. Appropriate selection of options relating to algorithms, objective functions, conditional constraints, parameters, etc., plays an important role in reaching system wide optimization. This paper suggests a knowledge-based approach to improving optimization techniques in system planning through a knowledge-based implementation of the options. The concept of knowledge-based hierarchical optimization in a planning process is presented to described the need for applying knowledge-based methodology to optimization consideration of system planning.

A knowledge-based implementation of the optimal power flow-based static security assessment of power systems, as an example of system planning, is presented to improve the traditional implementation of static security assessment. An expert system designed to the knowledge-based scheme of static security assessment has been described. Test results verified the feasibility of the scheme including the expert system used for implementing the scheme.

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