Development of a Hybrid Knowledge-Based System for Multiobjective Optimization of Power Distribution System Operations

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Abstract

The development of a hybrid knowledge-based system with a coupling between knowledge-based and numerical methods for multiobjective optimization of power distribution operations is described. The advantages of a hybrid knowledge-based system are described followed by the system objectives, means of control, and constraints. A framework is provided that describes the necessary development stages of a commercial knowledge-based package. An overview of the utility knowledge acquisition procedure is provided to appreciate the complexity of defining the rule base. This is followed by a description of the flow of information in a three-level hierarchical rule base and a summary of network radiality, parameter, and performance rules employed in this rule base. After a heuristic preprocessor identifies a list of switch closures that would seem to reduce total system losses, network radiality rules assess if a particular search path has identified a switch that can be closed and a corresponding switch opened to maintain the radiality of the system or if the path is worth pursuing further. Network parameter rules ensure the system operates within original design parameters. Network performance rules assess the reduction in total system losses of each proposed switching operation. Where there is a coupling between knowledge-based and numerical methods, the integration of numerical methods is described. Finally, the validation and simulations as well as the benefits of this hybrid knowledge-based system are described.

Introduction

Knowledge-based or numerical methods can be used in optimization of power distribution system operations. An extensive study of software tools used in real-time power system applications concluded that electric utility companies were not satisfied with conventional approaches based on numerical methods in 50% of the cases examined [1]. Dissatisfied parties cited two major shortcomings in techniques based on numerical methods:

1. lack of flexibility in system modeling
2. exclusion of operators' input in the decision making process

While algorithmic numerical methods will generally offer superior system optimization results, their solution times are often excessive. The algorithmic model may not include crucial system dependent information that can only be described with linguistic rules.

Knowledge-based methods are an efficient means of optimizing power distribution system performance [1-5]. A knowledge-based method offers the advantage that it employs heuristic and factual information derived from knowledge of the system behavior. From an engineering perspective, the integration of heuristic rules into the proposed reconfiguration method bridges the gap between abstract theory and an industrially viable tool. However, there is a serious shortcoming of knowledge-based methods in an application such as optimization of power distribution operations. An exhaustive search procedure such as a branch-and-bound strategy is typically employed to obtain a solution. An exhaustive search procedure to optimize performance of even a small distribution network would require a considerable amount of time. System optimization techniques based solely on knowledge-based methods suffer from numerous shortcomings:

- Examination of branch exchange is fast, but will most likely offer only a poor local optimum.
- Efforts to retain a radial network may limit the permutations and combinations of switching operations that can be considered.

Through a coupling of knowledge-based and numerical methods, the shortcomings of the individual techniques are overcome.

A hybrid knowledge-based system with a coupling between knowledge-based and numerical methods combines the advantages of both methods for multiobjective optimization of power distribution system operations. In addition to including existing numerical methods, it embodies all existing qualitative knowledge of the system. One must wonder why the hybrid knowledge-based system is not more widespread in industry.

The intelligent optimization system effectively optimizes a power distribution network for multiple system performance objectives:

- system loss reduction
- transformer load balancing
- reduction of transformer aging to decrease the failure rate and increase continuity of service
- maintenance of a satisfactory voltage profile throughout the network
- reactive power compensation
- conservative voltage reduction (CVR) practice to achieve peak shaving

The intelligent optimization system offers the following means of control:

- automated tie and sectionalizer switches
- transformer tap changers
- switched capacitor banks

The optimized network complies with a comprehensive list of constraints:

- network radiality
- line section and equipment capacity
- maintenance of acceptable fault current levels
- service priority for critical customers

Development of a Knowledge-Based System

The typical development process for a commercially viable knowledge-based system is as follows [6]:

1. project selection
2. investigation
3. analysis
4. design specification
5. implementation
6. evaluation
7. monitoring
8. maintenance

The work described has traversed all stages of this framework up to and including the implementation. The evaluation, monitoring, and maintenance stages are performed once the knowledge-based system has been integrated into a utility supervisory control and data acquisition (SCADA) system. Evaluation and monitoring are only possible once one analyzes the subtle characteristics of system performance.

Prior to describing the rule base, the knowledge acquisition process is described to show the complexity of defining a knowledge base. The effectiveness of the knowledge-based application relies heavily on the successful conceptualization of rules.

Utility Knowledge Acquisition for a Knowledge-Based System

Knowledge acquisition and conceptualization are formidable tasks. For this reason, end users (that is, control room operators or plant personnel) should be actively involved in the development process and not merely employed as a source of knowledge. As operational personnel become more involved in the development of the knowledge-based system, they will become more familiar with the type of information that must be recorded in the knowledge base. As the user interface on knowledge-based system software tools becomes more user friendly, in-house development of a complex knowledge base will become feasible.

Having established that a proactive involvement of operational personnel is necessary, the engineer or knowledge-based system developer directs the knowledge acquisition process. Knowledge can be acquired from computerized data collection, formal or informal interviews and information collection sessions, or written questionnaires. Automated intelligent knowledge acquisition tools [7] have the ability to pose increasingly appropriate questions to build a better knowledge base. However, using these knowledge acquisition tools may not be justified to support a simple application that is to be implemented on a programmable logic controller (PLC). Written questionnaires do not permit inclusion of a larger number of people in the search process and will yield considerable redundant information.

The interview process by the engineer should involve more than merely meeting with the expert in the confines of a conference room or office. The knowledge acquisition process should be performed at the site of the proposed knowledge-based system. Interview subjects should be aware that this technology will not threaten their jobs, but rather permit them to perform daily tasks with increased ease and safety.

Fig. 1 shows the groups of people that must be involved in development of the knowledge base and how their expertise is employed in this process. The knowledge acquisition process starts with discussions with management to identify both written and unwritten objectives of the proposed knowledge-based system development. Once the mandate of the development effort is understood beyond the scope of the written proposal, the engineer can direct the effort toward the desired goals. All personnel who may be familiar with the process or system behavior should be queried through some means. The dashed line in Fig. 1 symbolizes the fact that all operations, maintenance, engineering, and planning personnel of all levels of experience possess some type of expert knowledge and should be involved in the knowledge acquisition process. In the review process, the engineer finds the most applicable methods of

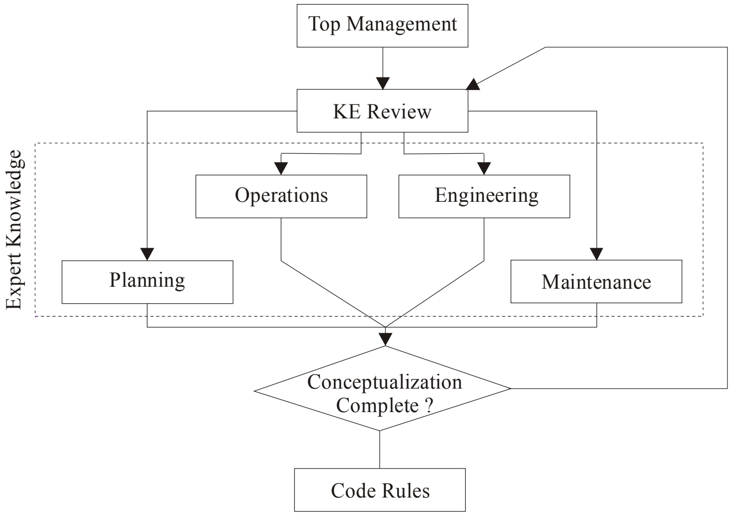

Fig. 1. People involved in knowledge conceptualization

knowledge acquisition. This review is an ongoing process until the knowledge-based system is developed to the stage that it can be integrated into operations. After each revision of the knowledge acquisition process, the approach is modified to assure that knowledge is complete.

Once a preliminary knowledge base has been acquired and processed, software implementation of the rules can proceed. Introduction of a preliminary prototype to potential users will yield further insight into system behavior. The development process never ceases. Once operations personnel are comfortable with the knowledge-based system, it may be used, but maintenance will constantly be required to account for changes in the system or operational practice. Prior to implementation, it is recommended that a rigorous validation procedure should be followed, as described in detail in [8].

The core of the multiobjective optimization system relies on a knowledge base determined from an expert appreciation for system behavior. While the subject of knowledge engineering may superficially appear to be somewhat intuitive, identification and definition of a complete set of rules quickly becomes a formidable task. A structured knowledge acquisition procedure is essential to defining a knowledge base that accurately represents the network.

Network Optimization Heuristics

There are three types of rules in a three-level hierarchical rule base in the hybrid knowledge-based system:

1. network radiality rules
2. network parameter rules
3. network performance rules

The extremely powerful CLIPS language [9] was used in the development of the knowledge base. The hierarchy of rule activation is illustrated in Fig. 2.

A three-tiered hierarchy is built into the rule base. Rules relating to radiality and operational parameters are assigned a higher saliency such that network radiality must first be satisfied followed by network operations criteria and then network performance. If radiality constraints are not satisfied, it is futile to examine network parameter constraints or the desirability of proposed control operations for performance enhancement. Once all radiality and operational parameter constraints are satisfied, an assessment is made of the degree to which the multiple objectives are enhanced by proposed control actions.

As indicated in Fig. 2, a good starting point is obtained from a heuristic preprocessor based on network partitioning theory like that described in [10]. The good starting point is a list of switch closures that would seem to reduce total system losses. It is necessary for the hybrid knowledge-based system to examine each member of the candidate list, identify which associated switch must be opened to preserve radiality, and determine if this will improve the desired performance characteristics. If one of the switches that was initially opened can be closed while preserving radiality, then the network parameter rules are activated. If the network parameter rules find that the switching operation will not violate the operational integrity of the network, an assessment of performance enhancements can be made with the network performance rules. In the event that either the network radiality or operational constraints are violated, the switching operation is assessed to be unacceptable. After the load is transferred, numerical methods are used to update network parameters.

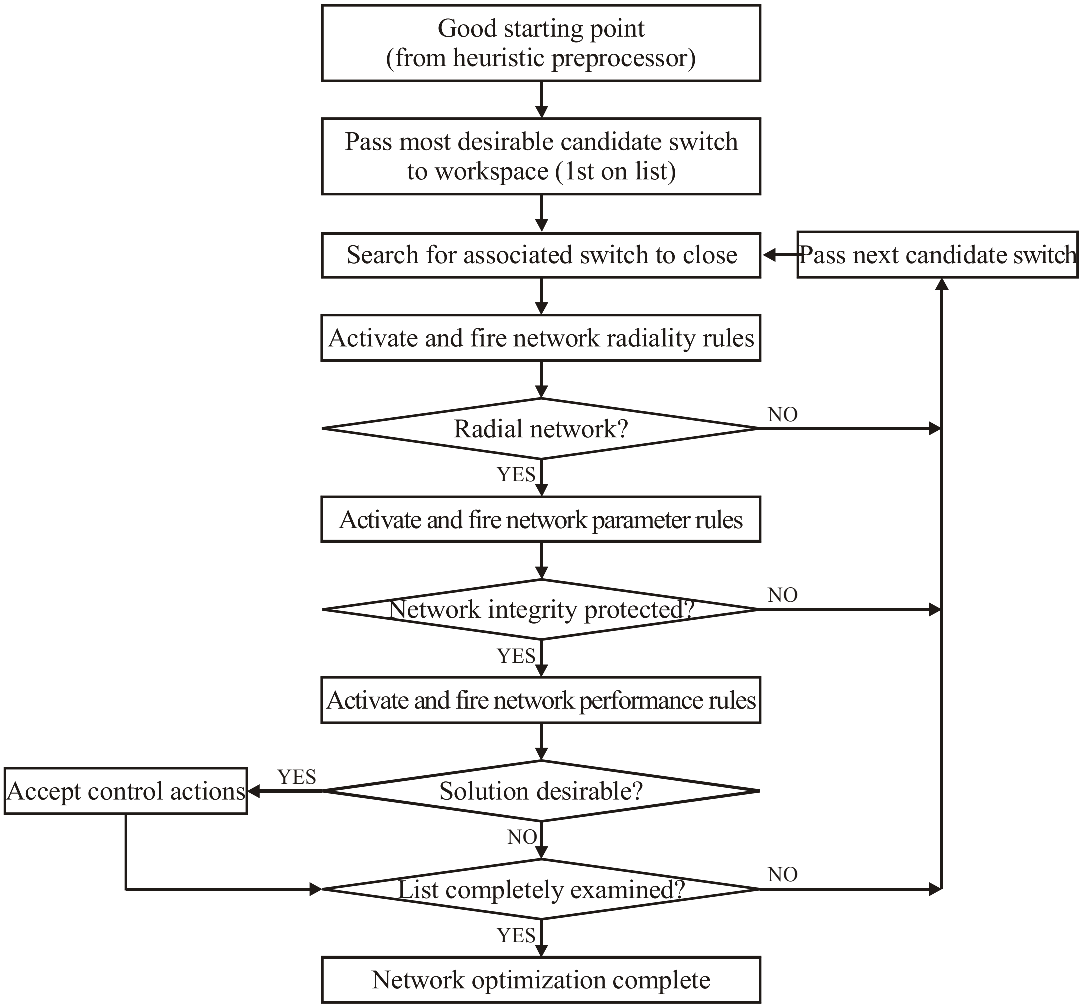

Fig. 2. Hierarchy of rule activation

Regardless of the outcome of a candidate switching operation analysis, the subsequent recommended switch opening on the list is used. Once the list of candidate switches has been completely examined, the system performance is considered optimized. Fig. 2 shows the search procedure for candidate switching operations. While determination of algorithm completion is based on examination of switching strategies, manipulation of switched capacitors and transformer tap changers is performed within the rules. Fig. 2 demonstrates how the good starting point is massaged to obtain a solution that optimizes multiple conflicting objectives. A summary of the heuristic rules in the hybrid knowledge-based system follows.

Network Radiality Rules

The most frequently used design for power distribution systems is the radial distribution system because it is the simplest and least expensive system to build. A radial distribution system has power lines extending radially from a common substation with customer loads coming off at single nodes along the line. A radial distribution system has only one power source for a group of customers and a power failure will interrupt power to all customers along the entire line. Power can only flow in one direction from the substation to the load. Network radiality refers to maintaining this power flow to all customer loads on a line. Ring distribution systems, also known as loop distribution systems, and network distribution systems are more expensive to build, but are more reliable because customers have more than one available power source. However, due to high capital and conversion costs, the majority of utility power distribution systems in service and under construction are radial in nature.

The primary concern of radial distribution network operation is to ensure a reliable and continuous supply of power to a distribution system and ensure that line current and fault current levels do not increase beyond system design parameters. Network radiality heuristics identify a pair of switching operations that will preserve radiality. A branch exchange is performed in which closing one line section results in the opening of another. A branch exchange can be somewhat inefficient in terms of solution time if not initialized by a good starting point, but can be employed in knowledge-based methods. The heuristics defined in the distribution system reconfiguration method of the hybrid knowledge-based system start by opening a switch on a meshed network. Line sections equipped with a switch are recognized and the required switch closing, associated with the switch opening proposed by symbolic optimization, is found. Radiality is ensured, even though the system is initially represented as a meshed network.

The search for the appropriate initially open switch to close is started by passing a switch to be opened from the good starting point list. Every switch has an upstream (supply) side and downstream (demand) side. When opening a switch, its upstream terminal switch will remain supplied with electricity. However, for the switch's downstream node, it is necessary to transfer the load to another substation. Network radiality is maintained by closing an associated initially open switch to assume the load transfer necessitated by the switch opening. Once the downstream node has been identified, several simple steps are followed to identify the switch, if one exists, that must be closed. The search path followed by the algorithm is retained in memory to update entries of line section and bus tables if an operation is identified. The connectivity of downstream nodes in the bus table is examined. The supply line of the downstream node no longer acts as a supply. By examining demand lines using network radiality rules, it is determined if the switch to close is in the current search path or another search path. If the search path is not disqualified, then it is stored in memory and the line section connected to the downstream node is examined; this is called the *trace-back path.* Once all possible line sections connected to the downstream node are examined, the optimization system commences examining the node on the other terminal of the line sections previously analyzed that are still on a viable search path. In this manner, a breadth-first search is performed. Due to the nature and tree-like structure of the distribution, it is thought that a breadth-first search would be more efficient than a depth-first search. If a switching combination is identified that will preserve network radiality while satisfying network parameter and network performance rules, then line section and bus tables are updated to ensure that appropriate network modifications are considered for subsequent analysis.

A summary of the network radiality rules follows. They are described in more detail in [11]. These network radiality rules are used to assess whether a particular search path has identified a switch that can be closed, or if the path is worth pursuing further.

Rule 1.1: Switch Existence.
If the line section to be cut is a switch, **then** the line section is a candidate.

Rule 1.2: Source or Terminal Line Section.
If the line section is a source or terminal section, **then** the line section is not a candidate.

Rule 1.3: Previously Open Switch.
If the line section was previously used in the optimization, **then** the line section is not a candidate.

Rule 1.4: Connection to Initially Open Switch.
If the downstream node is connected to an initially open switch **and** an initially open switch has been found, **then** a switching combination has been identified.

Rule 1.5: Validity of Extreme Node—Redundancy.
If the extreme node of the initially open switch has supply, **then** the line section and initially open switch are candidates.

Rule 1.6: Formation of an Isolated Loop.
If the source trace from the extreme node does not cross the trace-back path, **then** the line section and initially open switch are candidates.

Network Parameter Rules

If conditions for a radial network are satisfied, then network parameter heuristics, which are next in the rule hierarchy, are activated. Network parameter heuristics ensure the system operates within the original design parameters. Also, they ensure that a minimal voltage level is supplied to customers and that optimal VAr compensation is performed by manipulation of switched capacitors. These criteria must be satisfied as part of the optimization of system operation. A summary of the network parameter heuristic rules follows:

Rule 2.1: Ensure Acceptable Fault Current Levels.
If the switching operation includes existing switches, **then** the fault current level remains acceptable.

Rule 2.2: Line Section Capacity.
If the load transfer is within line ampacities, **then** the switching combination is acceptable.

Rule 2.3: Equipment Capacity.
If the load transfer is within equipment ratings, **then** the switching combination is acceptable.

Rule 2.4: Transformer Aging Due to Temporary Transformer Overloading.
A table of typical loading guidelines is stored for each transformer. This is essential as the guidelines are established for a 24-hour period. The actual transformer loading is considered up to the actual time of day, but for the remainder of the day a load projection is made using the typical loading guidelines stored for each transformer. The information passed to a transformer aging routine includes actual and projected transformer loading in per unit of transformer rating for each hour on a 24-hour basis as well as ambient temperature. Then the loss of life is calculated iteratively over a 24-hour period.
If a transformer is overloaded by a load transfer, **then** perform transformer aging calculations.

If the emergency condition and emergency aging limit are respected, **then** the overload is acceptable.

Rule 2.5: Daily Transformer Aging.
If the load is transferred to a transformer, **then** perform transformer aging calculations.
If daily aging limits are respected, **then** the switching combination is acceptable.

Rule 2.6: Minimum Voltage Requirements.
A voltage update routine is employed that either steps up the transformer taps for voltage correction or steps down the transformer taps for CVR until the desired objective is attained. Bus voltages are updated using the ladder network technique.
If the bus voltage is at an acceptable level, **then** the switching combination is acceptable.
If the bus voltage is lower than the acceptable level, **then** invoke the voltage update routine.
If the voltage update routine is executed and the bus voltage is lower than the acceptable level, **then** the switching combination is unacceptable.

Rule 2.7: Adjustment of Reactive Power Compensation.
If the load is transferred to a substation and the main feeder is equipped with switched capacitors, **then** switch in capacitors according to the 2/3 rule.
If the load is shed by a substation and the main feeder is equipped with switched capacitors, **then** switch out capacitors according to the 2/3 rule.

Rule 2.8: Service Priority.
If a priority customer is supplied by several service entrances, **then** the customer is to be supplied by two different utility substations.

Having gained a better understanding of the network parameter heuristics, it is evident that satisfaction of these heuristics will in itself lead to improved system performance. Criteria such as voltage level or optimal capacitor switching are very rarely considered by the typical municipal utility.

Network Performance Rules

Once the network parameter heuristics are satisfied, network performance heuristics are activated to optimize performance of the system. The assessment of a switching operation in reducing total system losses is a somewhat complicated procedure. A set of rules has been defined to provide a qualitative assessment of each switching operation to overcome the burden of the time-consuming numerical methods that would be required to determine the exact value of loss reduction. The task of CVR operation is at the leading edge of power systems operation; the network performance heuristics have the facility to perform CVR operation.

Rule 3.1: Loss Reduction Assessment through Voltage Drop.
If $\Delta v_{sub\ 1\text{-}a} > \Delta v_{sub\ 2\text{-}b}$, **then** transfer bus A to substation 2.
If $\Delta v_{sub\ 1\text{-}a} < \Delta v_{sub\ 2\text{-}b}$, **then** do not transfer bus A to substation 2.
where bus A is connected to substation 1, bus B is connected to substation 2, $\Delta v_{sub1\text{-}a}$ is the voltage drop from substation 1 to bus A, and $\Delta v_{sub2\text{-}b}$ is the voltage drop from substation 2 to bus B.

Rule 3.2: Conservative Voltage Reduction (CVR).
After initial analysis, the voltage update routine will decrease tap settings until either the bottom tap is reached or range B (tolerable zone) is achieved from range A (favorable zone). Range A is from 96-110% of nominal voltage, and range B is roughly from 90-95%. These voltage levels are based on ANSI loading guidelines [12].
If $\Delta v_{sub\ 1\text{-}a} > 0.95*\Delta v_{max}$, **then** maintain the current tap setting.
If $\Delta v_{sub\ 1\text{-}a} < 0.95*\Delta v_{max}$, **then** incrementally lower the tap setting until the desired voltage is achieved.
where Δv_{max} is the maximum voltage drop; this value is multiplied by a factor of 0.95 as a safety margin against possible approximation error.

Rule 3.3: Heuristic Indices.
Sarfi et al defined two heuristic indices that calculated the desirability of a switching operation [13] based on voltage, power flow, and impedance parameters from both the open and closed switches of the switching pair. Indices C_1 and C_2 represent the most desirable and least desirable switching operations, respectively. An index value of 0 identifies an undesirable switching operation. An index value of 1 identifies the most desirable switching operation.
If $C_1 < 0.25$, **then** the switching combination does not reduce losses.
If $C_2 > 0.75$, **then** the switching combination is a candidate.

Rule 3.4: Overall System Loss Reduction.
If the switching combination reduces losses, **then** total system losses will be reduced by that amount.

Rule 3.5: Conversion Criteria.
If the overall system loss is reduced and all network parameter and network radiality rules are satisfied, **then** recommend control actions.

Validation and Simulations

The intelligent optimization system was validated and simulated on a subsystem of an actual 4.4 kV radial distribution network with approximately 70 load points including 14 major customers of the commercial, industrial, or multiunit residential types. The network was supplied by two substations, each equipped with an identical 5 MVA transformer. The network was equipped with 31 switches of which 20 were to be employed in the system optimization method. An extensive validation of the intelligent optimization system during the time of highest system demand on the test network indicated that system constraints were never violated by the optimization system software and all performance characteristics were enhanced. There was an improved voltage profile, reduced line section loading, and diminished transformer aging.

Extensive simulations were performed covering operation of the power distribution system over a year including summer weekdays, summer weekends/holidays, winter weekdays, and winter weekends/holidays. Residential, commercial, industrial, and mixed load types were represented in the simulations. Simulations showed that the optimization of power distribution system operations can be significantly enhanced through the use of automated tie and sectionalizer switches, transformer tap changers, and switched capacitor banks. Simulations further revealed that optimization solutions are found in a time-efficient manner while significantly enhancing performance, achieving all objectives, and producing significant monetary savings.

Conclusion

After a heuristic preprocessor identifies several switch closures that would reduce system losses, network radiality and parameter heuristics identify those switch openings that would preserve radiality and system operational criteria, respectively. Network performance heuristics assess the capability of a proposed operation to optimize specific objectives. Both qualitative and quantitative rules are included in the proposed system optimization technique to ensure that proposed system changes will not compromise the integrity of the network or violate principles of sound engineering practice. All operational aspects of power distribution systems have been considered in the proposed system optimization method and a solution is still obtained in real time.

The development of this hybrid knowledge-based system employing knowledge-based and numerical methods to perform a multiobjective optimization of power distribution system operations is a giant leap forward in the research literature [1, 2]. Previously published approaches do not optimize for as many objectives, offer as many means of control, comply with as many network constraints, and combine knowledge-based and numerical methods. The definition of heuristic rules for network radiality, network parameters, and network performance is in itself a substantial contribution to power systems theory. This is illustrated by the description of complexity in utility knowledge acquisition and conceptualization. Another distinct advantage associated with this synergetic performance optimization method is that no aspect of system performance will be worsened under any circumstances.

These optimization methods based on the synergy of knowledge-based and numerical methods can decrease system losses, thus resulting in a more energy efficient system and less burning of non-renewable fossil fuels (coal, oil, and natural gas) to generate electricity. Less burning of fossil fuels leads to reduced global warming [14], decreased air pollution and acid rain, diminished dependence on foreign oil, and reduced harm to the environment and wildlife from obtaining fossil fuels. Reduced global warming elicits diminished severity of natural disasters caused by global warming, less extreme weather, diminished spread of infectious diseases, and less loss of life. Decreased air pollution and acid rain induce fewer health problems, less harm to plant and aquatic life, and reduced damage of materials. Diminished dependence on foreign oil reduces skewing and inequities in foreign policy. In nuclear power plants, there would be diminished uranium consumption and hence less nuclear waste. Furthermore, the methods described can increase transformer life spans and enhance the reliability of a power distribution network. This can prevent power outages, which cost individuals and organizations tremendous productivity, time, and money. Decreased consumption of fossil fuels or uranium and increased transformer life spans lower operating costs and consumer prices.

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