Loss Reduction in Distribution Networks using Concurrent Constraint Programming

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***Abstract*— This paper presents a new technical losses reduction model in an electrical energy distribution system by using network reconfiguration technique. First-order logic is used as the model specification language. This specification is easily translated into programmable sentences in the CCP (Concurrent Constraint Programming) paradigm. Unlike other existing methods in the literature, this model includes both the system operating constraints and the electric laws related to load flow. The CCP paradigm takes advantage of the interaction between these two types of constraints to reduce significantly the search tree, in contrast with the iterative methods used traditionally. In turn, it does not require the constraints verification once the solution is found. The tool developed has been tested for simulating small cases up to 50 nodes, obtaining good accuracy and running times. The power flow results were validated against NEPLAN results and the reconfiguration results were compared to those obtained with three different tools developed by other authors.**

***Index Terms*— Concurrent Constraints Programming (CCP), Constraint Satisfaction Problem (CSP), network reconfiguration, power losses reduction.**

I. Introduction

Ideally, losses in an electric system should be around 3 to 6%. In developed countries, it is not greater than 10%. However, in developing countries, the active power losses percentage is around 20%; for this reason, utilities in the electric sector are currently interested in reducing it in order to be more competitive, since the electricity prices in deregulated markets are related to the system losses. In the Valle del Cauca region in Colombia, in 2001 the technical and non-technical losses were accounted as 12% of the total input energy.

To manage a loss reduction program in a distribution system it is necessary to use effective and efficient computational tools that allow quantifying the loss in each different network element and finding a suitable configuration for system losses reduction. In the losses reduction method using reconfiguration for two 500-bus circuits and 10 flexibilization systems, there would be $4{,}91\text{x}10^{41}$ possible configurations [37]. Assuming evaluation of a million alternatives per second, finding the optimum configuration by analyzing all of them would take $1{,}55\text{x}10^{28}$ years. Search methods that reduce considerably the number of configurations to evaluate and obtain good (if not optimal) losses reductions are thus highly needed.

Losses reduction using the reconfiguration technique is an active research problem involving complex issues: nonlinear objective function, a huge combinatorial space due to the distribution system size, a large number of continuous and discrete variables, and operating constraints compliance.

An important difference between the scheme proposed in this paper and existing solutions for the losses reduction problem using reconfiguration is that, in the latter, constraints are only used for testing the feasibility of proposed configurations, whereas in our approach they are used as active devices for reducing the search space and for controlling the search strategy. Furthermore, being a complete inference procedure, our approach allows us to compute all feasible solutions, in contrast with heuristic techniques traditionally used. The main contribution of this paper is to show that network reconfiguration can be effectively achieved by simply stating an exact model of both electric laws and operating conditions directly in a CCP framework.

II. Computational Methods for Losses Reduction

Network reconfiguration was first proposed as a research topic in 1975 by Merlin & Back, engineers at Electricité of France. Power losses minimization is modeled -without including operating constraints- as objective function.

Between 1988 and 1990 the heuristic methods were used to solve the problem. The developments during this period were focused on increasing the number of operating constraints. From 1990, new solution strategies appeared: linear programming, simulated annealing, and genetic algorithms, whose objective function is power losses minimization and the operating constraints previously used. In addition, load models are improved with more precise models.

In 1993, solutions to the problem were presented through neural networks, which initially model few operating

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constraints and simple load models. In 1997 models with more constraints were used. Between 1995 and 1996 the heuristic method was proposed again in order to optimize energy losses using more precise load models. From 1997 until now, the techniques used are combinations of the previous techniques, aiming to complement each method's strengths.

According to the historic development, the computational searching methods are classified into three large groups: Knowledge-based methods, methods based on evolutionary techniques and mixed methods.

A. Knowledge-based methods. They are based on the operators' experience in the system operations. Based on this knowledge, algorithms have been designed to facilitate searching for the new distribution network configuration, trying to find an option close to the optimal. Heuristic methods, linear programming, expert systems and fuzzy logic are under this category.

B. Methods based on Evolutionary Techniques. They are based on imitation of physical, biological and neurological processes present in nature. They have as an important characteristic: the lack of a rigorous mathematical formulation that allows establishing their operation in each situation with certainty. Examples of techniques in this category are: simulated annealing techniques, genetic algorithms and neural networks. These techniques start from a solution and improve it.

C. *Mixed Methods.* These methods are in use since 1996 and are combinations of previous methods to gather their combined strengths; hence better results are obtained.

Table 1 illustrates the historic development of the different methods and evaluation items; this allows comparing the different methods. (Numbers represent rate satisfaction: 1 represents good, 2 fair and 3 poor).

III. WHAT CONCURRENT CONSTRAINT PROGRAMMING (CCP) IS?

A great variety of combinatorial problems can be expressed as searching for one or several elements in a vast space of possibilities. In general, the search space is defined as all combinations of possible values for a predefined set of variables. Elements to be searched for are particular values of these variables. In most cases the desired values of the elements are implicitly specified by properties they should meet. These properties are known as *constraints*, which are usually expressed as predicates over some set of variables. Roughly speaking, a problem formulated in this frame is known as a Constraint Satisfaction Problem (CSP). Solving a CSP using Concurrent Constraint Programming (CCP) languages, consists of two steps: modeling the problem (logical specification) and specifying the search strategy for finding its solutions. Modeling involves basically writing in the concurrent constraint programming language the variables, their domains and the constraints among them.

In the CCP paradigm a procedure, called a propagator, is associated to each constraint. This procedure tries to reduce the domain of the variables associated to it (i.e. it discards values of the domains of the variables that can not be part of any solution.)

The collection of propagators acting on the variables may cause a domain to become empty. This means that the problem specification is contradictory and so there is no solution. Propagators may instead reach a fixed point state in which nothing new about the variables can be deduced (i.e. the domains cannot be further reduced). In that case, a search stage is necessary.

Specifying the search strategy consists in defining the criteria for the search when the propagation has taken computation to a fixed point state in which undetermined variables (i.e. those having domains with more than one value) remain. The main idea is to add to the current fixed point state one or more constraints that allow the propagation process to advance a little bit more (i.e. allowing it to reduce some domain of some variable.) Since these constraints are not part of the problem constraints, it is also necessary to explore what happens if the opposite constraints are added to the fixed point state. In that way all possibilities are taken into account and no solution is missed. The process of adding these new constraints is called *distribution.*

The search strategy specifies the constraints that must be added; whatever they are, adding them creates two new search states. In each of them, the propagation process is applied again until a new fixed point state is reached and the procedure is repeated. If all variables are determined, a solution has been found. If, after exploring all possibilities, all states are contradiction states, then the problem does not have a solution.

The efficiency of the search is directly linked to the number of explored states. The more the domains of the variables in the propagation stage are reduced, the less states are generated and, therefore the problem is solved more quickly. The number of generated states also depends on the distribution strategy.

Asserting redundant constraints (e.g. those eliminating problem symmetries) is a frequently used strategy for increasing search efficiency.

Searching for the best solution in the CCP model uses a branch and bound technique. A valuation (in this case, amount of power losses) of a previously found solution provides a lower bound. A constraint asserting that the next solution must have a better valuation than the lower bound is then added. This constraint has also an associated propagator that further reduces the search tree.

Using the CCP paradigm thus in general leads to smaller search trees. Furthermore, the tree rarely has to be traversed exhaustively, even when all possible solutions must be computed.

Table 1. Reconfiguration Methods Comparison

Methods Classification	**Method**	**References**	**Evaluation Indexes**						
			Large systems	% losses reduction	General Application	Flexibility	Running Time	Constraints Management	Model Precision
Knowledge Based (1975)	Heuristics	1,2,3,4,5,7,9,10,11 12,13,24,25,27,28, 33,34	1	2	1	2	1	2	2
	Linear Programming	16,22	3	2	1	3	3	3	3
	Expert Systems	29	1	3	3	2	3	3	3
	Fuzzy Logic	20	1	3	1	2	1	2	3
Evolutionary Techniques Based (1990)	Simulated Annealing	6,7,14	3	1	1	3	3	2	2
	Genetic Algorithms	18,19	3	1	1	3	3	2	2
	Neural Networks	30,31,32	3	3	3	3	1	3	3
Mixed Methods (1997)	Linear Programming + Heuristics	8,26	3	2	3	3	1	2	3
	Genetic Algorithms + Fuzzy Logic	21	3	2	1	3	1	2	3
	Fuzzy Logic + Heuristics	23	1	2	1	3	1	2	3
	Simulated Annealing + Heuristics	17	3	2	1	3	1	2	3

The efficiency of CCP paradigm depends greatly on the propagation ability of the constraint system propagators. The greater the capacity, the less the branch generation and therefore the greater the efficiency.

Existing constraint systems for finite domains (i.e. finite sets of natural numbers) are able to efficiently perform strong domain reductions. Constraint systems over the real numbers are less well understood. For the reconfiguration problem reported here, we built an advanced constraint system for the real numbers using interval arithmetic.

IV. CCP FOR COMPUTING LOSSES REDUCTION

The key for using CCP is viewing Load Flow Computing and Reconfiguration as CSP problems.

Load Flow Computing can be seen as searching for buses voltage values and current branch values satisfying a set of equations (constraints) corresponding to the electric laws (Kirkchoff and Ohm, for example).

On the other hand, reconfiguration can be seen as searching for branch switches values (open or closed) satisfying operating constraints (system radiality, service continuity, voltage quality, thermal limit in any branch and power transformer, minimum and maximum limit of switching operations) and such that its corresponding load flow problem has a better solution than the initial configuration. In this case, operating and electric constraints are integrated in a natural manner.

Once these problems are formulated as CSP problems, we can use a CCP Language for solving them. In our case we use Mozart (see http://www.mozart-oz.org). Results are shown in next section.

V. SPECIFYING THE PROBLEM IN THE CCP MODEL

Computing load flow requires complex numbers. As usual, each complex was represented with two real numbers. We could interpret these as belonging either to a rectangular or to a polar form. With the former, electric laws and operating conditions become polynomial constraints, whereas with the latter they are expressed as trigonometric constraints. Since the propagators for polynomial arithmetic over real numbers are known to be stronger, more robust and more efficient than trigonometric propagators, we chose the rectangular representation of complex numbers. Of course, we could have used both (redundant constraints, in general, are supposed to help pruning the search tree), but in our tests using both representations proved to be more a hindrance than an advantage: the search tree was indeed smaller with both set of constraints, but the total computation time actually increased, due to the additional domain narrowing computations. A second issue is that logic variables (i.e. single assignment variables) are used in the CCP model. We thus associated two logical variables to each electric variable, one for the original configuration (subscripted "o") and one for the final configuration (subscripted "f").

A. *The constraint implementation.*

Ohm laws (real and imaginary components) are written in Mozart as follows:

```
{XRI.hc4 eq(sub(V1_real V2_real) sub(times(I_real R)
                times(I_img X)))}
{XRI.hc4 eq(sub(V1_img V2_img) plus(times(I_real X)
                times(I_img R)))}
```

Procedure XRI.hc4 constructs a propagator for a given constraint using an efficient algorithm called HC4. The argument to this procedure is a constraint expressed in prefix notation (i.e. each operators appear before its arguments). Variables V1_real and V2_real, V1_img, V2_img stand for real and imaginary components, respectively, of bus voltages. Similarly, I_real and I_img are real and imaginary components of branch current. Variables R and X denote resistance and reactance, respectively. Propagators for Kirchoff laws, including branch and load currents, are similarly expressed. Operating constraints are expressed as follows:

```
{XRI.hc4 leq(sqrt( plus( square(Io_real) square(Io_img) ))
         times(CCR plus(1.0 PsCPR)))}
```

This constrains the magnitude of the current in each branch to be less than or equal a given factor (CCR) of a limiting operating percentage (PsCPR). Procedure HC4 is also used for constraints involving losses computation in each branch:

```
{XRI.hc4 eq(Io_losses times(R plus(square(Io_real)
         square(Io_img))))}
```

Losses in all branches are then accumulated (variables Tlo and Tlf). The "objective function" of a reconfiguration is then expressed as the constraint:

```
{XRI.hc4 leq(Tlf sub(Tlo MinImprovement)}
```

which says that total losses of the reconfigured network (Tlf) should improve the original (Tlo) by at least a given value (MinImprovement).

The above procedures handle load flow computation. Reconfiguration is performed by setting switch state variables, These are boolean variables indicating open or closed states. Each node in the network has an associated variable whose value identifies its feeder. Whenever a state switch is set, variables for the end points of the switch are constrained to be equal. If a contradiction results, the network is not radial. A final constraint controls the number of switching operations:

```
{FD.atMost NumChanges MaxChanges 0}
```

This uses a built-in finite domain propagator asserting that the difference between the number of switching operations performed and the maximum allowed must be at most zero. The distribution process searches switches first, then currents and lastly voltages. We did not use any heuristic strategy to select the ordering of the branches in the net. Nevertheless, those employed, for example, in (REFERENCIA CIVANLAR) could be easily accomodated in the distribution strategy. Distribution of switch state variables is implemented as follows:

```
{FD.distribute generic(order: size value: max) SwState}
```

This construct chooses switches in ascending order of its domain size (i.e. those already determined are handled first) and, for each switch, chooses first its maximum value (i.e. assumes it is closed). The distribution strategy is generic. Instead of "size" or "max", any user defined functions implementing better heuristics could be used. We are currently experimenting several options in this regard.

B. Mathematic Formulation

The formulation to find out a better configuration alternative that allows reducing power losses in a distribution network can be written as:

Objective function:

$$\forall R_j ; 1 \le j \le m$$

$$0 \le \sum_{j=1}^{m} R_j . Lp_f < \sum_{j=1}^{m} R_j . Lp_o$$

Where R represents the branches in the distribution network and Lp corresponds to the branch losses.

In the CCP paradigm, this objective function is set out as another constraint in which the new alternative must have less losses that the previous one.

Subject to:

1. Operating constraints:

- Voltage in feeder buses
- Voltage limit in internal buses
- Limit of current in branches
- Current limit in the power transformer
- Radiality
- Maximum switching operations limit
- Service continuity

2. Electric constraints:

- Ohm law in each of the branches
- Kirchhoff current law in each bus

C. Results

This section describes the results of feeder reconfiguration for some canonical problems like Civanlar [2] and Baran [3] using the concurrent constraint mentioned above and its implementation in the Oz programming language. The implementation uses the Mozart built-in finite domains constraint system to assign the state of the switches and the real intervals constraint system XRI to compute the load flow. As mentioned before, propagators for real intervals constraints stating electric laws and operational conditions interact with finite domain constraints controlling switch operations while maintaining radiality, in such a way that infeasible solutions are quickly discarded.

All tests were run on an Intel Xeon 2.40GHz computer with 1GB of RAM running Linux Gentoo 1.4 with kernel 2.4.20 and Mozart system 1.2.5.

- *Civanlar Example*

We found the active losses (0.0054 p.u.) for the initial topology of Civanlar in 740 ms using a precision of 10^{-5}. We then asked the system to compute all possible different reconfigurations achieving loss reduction and such that no more than 4 switching operations were needed. We found 6 different topologies in 3m 33s. Furthermore, in this case we also assumed that all branches had a switch, an assumption that might be very useful when trying to find the best location for each switch. Figure 1 shows a partial view of the reconfiguration search tree.

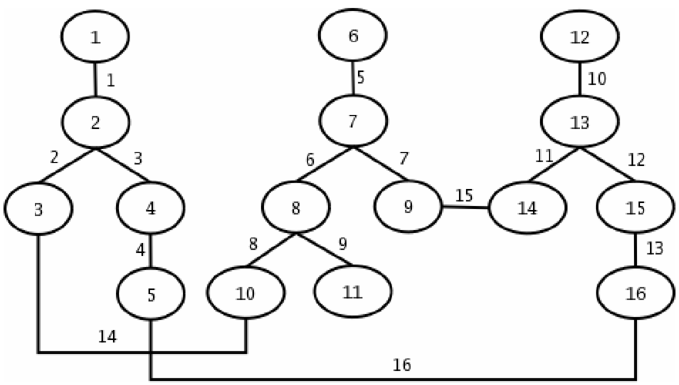

Figure 1. Reconfiguration search tree

Table 2 summarizes the reconfiguration results.

Active Losses [p.u]	% Gain	Proposed configurations
0.0052	3.70	Open 8 and close 14
0.0051	5.60	Open 7 and close 15
0.0053	1.85	Open 4,7 and close 15,16
0.0054	0.00	The initial topology
0.0054	0.00	Open 7,13 and close 15,16
0.0049	9.25	Open 7,8 and close 14,15– Best configuration
0.0053	1.85	Open 4,8 and close 14,15

Table 2. Results from Reconfiguration of Civanlar Case using CCP

Table 3 shows a percentage loss reduction and running times using the methods from references [33,35,36] and the one using CCP.

Method	Number of Switches	Losses Before (kW)	Losses After (kW)	% of Reduction	Running Time
1 [33]	1	514.04	485.78	5.49	00:00:00.01
2 [35]	2	510.56	464.90	8.90	00:00:00.05
3 [36]	2	514.04	485.78	8.89	00:00:00.08
4 [CCP]	2	542.48	496.67	8.44	00:00:01.33

Table 3. Percentages of loss reduction and Running Times

Methods 2, 3 and 4 propose the same configuration for loss reduction and the difference on loss reduction percentage is due to the results accuracy in the load flow algorithm used. In this work the numerical precision was 10^{-5}.

- *Baran Example*

In this case we obtained two new topologies (more could be obtained by clicking on some active node of the search tree) in 1m 25seg. The initial active losses were 0.00503 p.u. The two reconfigurations are shown in table W. Running time was 6m 20seg.

Losses (initial)	Losses (final)	Proposed configuration
0.00503	0.00477	open 48; close 53
0.00503	0.00495	open 1, 47; close 49,53

Table 3. Results from Reconfiguration of Baran Case using CCP

VI. CONCLUSION

In this paper, a formal model for network reconfiguration in a radial, balanced and 3-phase distribution system, using the constraint programming paradigm, is presented. The power transformer feeds a constant voltage bus, and in the primary network model, branch resistance and reactance are taken into account. Load modeling considers a constant power model.

The objective function that is going to be minimized is the reduction of active power losses in the network. In addition, operating constraints and electrical law constraints (load flow) are considered in the searching process. The objective function itself is expressed as an additional constraint in order to facilitate the search for a global minimum.

Using constraint programming paradigm as a new network configuration method implied a new conception of a radial power flow algorithm. The solution is not found by iterative calculation but by using searching the solution over trees where the answers are found. The search method used in this paradigm to get a better configuration does not require to build the searching tree but to select the tree exploration and the searching strategy. Furthermore, this searching model involves options that consider links within the same feeder.

This method offers some advantages such as ease of implementation, good losses reduction percentage, flexibility, constraints management and the possibility to use a GUI (Graphical User Interface) .

Although the reconfiguration method developed in this paper is generic, it has some drawbacks related to the application over large networks and the long running times. To overcome these deficiencies, it is planned to use numerical analysis techniques in the developed constraints system (XRI) and to build a more sophisticated distribution strategy that allows increasing the number of buses in the network.

One of the advantages of the CCP paradigm is the simplicity and flexibility to model the problem, that is, the constraints can be expressed exactly in the same language the user utilizes to conceive it; better yet, formulating additional constraints or eliminating them is not difficult at all. For this reason, the program that implements the solution to a problem can be easily adapted to new uses.

The CCP model involves all the restrictions within the search process and considers them as guides that show promising ways to a better solution. In addition, it allows integrating its exploration mechanisms (propagators) that reduce the search tree, with the heuristic rules that evaluate how ideal a partial solution is before generating it completely.

Constraint programming paradigm might be used in other power systems areas that require finding a solution by using searching trees such as power flows in meshed systems, network restoration after faults, contingency analysis and decision-making analysis.

The chosen language does not allow the direct use of complex numbers; therefore, they must be used as two real numbers, thus increasing the amount of equations in the mathematical model and in the operations. In addition, per each mathematical function required in the model, a propagator must be built, and that involves time.

On the other hand, the model's abstraction level makes the search process observation difficult but allows greater versatility when different strategies must be implemented.

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