ISSN(Online) : 2320-9801
ISSN (Print) : 2320-9798

International Journal of Innovative Research in Computer and Communication Engineering

An ISO 3297: 2007 Certified Organization Vol.5, Special Issue 2, April 2017

An International Conference on Recent Trends in IT Innovations - Tec'afe 2017

Organized by

Dept. of Computer Science, Garden City University, Bangalore-560049, India

Reconfiguration of Network for Loss Reduction in Three-Phase Power Distribution Systems

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ABSTRACT: In this paper the reconfiguration network problem is formulated as single objective optimization problem with equality and inequality constraints. The proposed solution to this problem is based on a general combinatorial optimization algorithm known as simulated annealing. To ensure that a solution is feasible it must satisfy Kirchhoff's voltage and current laws, which in a three-phase distribution system can be expressed as the three-phase power flow equations.

The simulated annealing algorithm is described in a general context and then applied specifically to the network reconfiguration problem. Also presented here is a description of the implementation of this solution algorithm in a C language program. These results provide the basis for the extension of existing methods for single-phase or balanced systems to the more complex and increasingly more necessary three-phase unbalanced case.

I.INTRODUCTION

In the past decade or so, with the advances in communication and data processing technology, electric utility companies have become very interested in *distribution automation.* It is apparent that with the increasing complexity of power distribution systems, it is becoming essential to automate some tasks that have always been done manually. It has also been estimated that utilities could save as much as 10% of their annual maintenance and operating expenses by taking advantage of this technology [3].

One important area in which distribution automation is being applied is the area of reconfiguration network. Reconfiguration network refers to the closing and opening of switches in a power distribution system in order to alter the network topology, and thus the flow of power from the substation to the customers. There are two primary reasons to reconfigure a distribution network during normal operation. Depending on the current loading conditions, reconfiguration may become necessary in order to eliminate overloads on specific system components such as transformers or line sections. In this case it is known as load balancing. As the loading conditions on the system change it may also become profitable to reconfigure in order to reduce the real power losses in the network. This is usually referred to as reconfiguration network for loss reduction and is the topic of this paper. Companies currently need an algorithm which can be applied to their large three-phase unbalanced distribution systems.

Three-Phase vs. Single-Phase Power Flow

For certain applications it is not necessary to take into account potential system imbalance, therefore it is sufficient to model the system as a balanced three-phase system. When this is the case, per phase analysis can be used to formulate a single-phase power flow problem.

However, it is not always possible to completely balance the system loads, and transmission line impedances can be unbalanced due to un-transposed lines sharing the same right of way. As distribution systems become larger and more complex, it becomes more important to take into account the system imbalance. Some of the effects of system imbalance, according to [2] and [4], are negative sequence currents causing problems with motors, zero sequence currents causing protective relays to malfunction, increased system loss, decreased system capacity, and an increase in inductive coupling between parallel lines and feeders.

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In any case, no power system is completely balanced and sometimes the additional complexity of a three-phase load flow study is necessary to model the system closely enough to accurately acquire the information of interest.

Three-Phase Power Flow Equations

Given a system with a total of n buses, define a bus voltage vector, V_{bus} , and a bus injection current vector, I_{bus} , as

$$V_{bus} = [V_1^a, V_1^b, V_1^c, V_2^a, V_2^b, V_2^c, \ldots, V_n^a, V_n^b, V_n^c]^T, \text{ and}$$
$$I_{bus} = [I_1^a, I_1^b, I_1^c, I_2^a, I_2^b, I_2^c, \ldots, I_n^a, I_n^b, I_n^c]^T \tag{1}$$

where V_i^p and I_i^p are complex values representing the voltage and injected current, respectively, of phase p at bus i. With the appropriate models for each of the system components, it is now possible to construct Y_{bus} , the system admittance matrix[1] which relates the bus voltages and currents according to Kirchhoff's voltage and current laws

$$I_{bus} = Y_{bus} V_{bus} \tag{2}$$

$Y_{bus} = [Y_{ik}^{pm}]$ is a $3n$ x $3n$ complex matrix whose element Y_{ik}^{pm} relates the
Z
AA voltage V^m_k to the current I_i^p.

The goal of the load flow study is to determine the values of the V_{bus} vector based on the specified network configuration and loading conditions. The representation of the power system network given by Equation (1) provides a framework for formulating the power flow equations and developing algorithms for solving them.

Simulated Annealing

The concept of simulated annealing was first introduced in the field of optimization in the early 1980's by Kirkpatrick et. al. [5; 6] and independently by Cerny [7]. Simulated annealing is a robust, general-purpose combinatorial optimization algorithm based on probabilistic methods which has been applied successfully to many areas such as VLSI circuit design, neural-networks, image processing, code design, and capacitor placement in power systems.

Combinatorial Optimization

A combinatorial optimization problem is a minimization or maximization problem which involves finding the optimal or "best" solution out of a set of possible alternatives. It can be completely characterized by the search space and the cost function or objective function.

Analogy to Physical Annealing

The name *simulated annealing* comes from an analogy between combinatorial optimization and the physical process of annealing. In physical annealing a solid is cooled very slowly, starting from a high temperature, in order to achieve a state of minimum internal energy. It is cooled slowly so that *thermal equilibrium* is achieved at each temperature. Thermal equilibrium can be characterized by the Boltzmann distribution

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$$P_T\{\mathbf{X}=x\} = \frac{e^{-E_x/k_BT}}{\sum_{\text{all states } i} e^{-E_i/k_BT}} \quad (3)$$

where X is a random variable indicating the current state, Ex is the energy of state x, kB is Boltzmann's constant, and T is temperature.

Table.1 Simulated vs. Physical Annealing

Optimization Problem	Physical System
solution x	current state of the solid
cost or objective value $f(x)$	energy of current state
control parameter T	temperature
optimal solution x_{opt}	ground state
simulated annealing	gradual cooling

The Simulated Annealing Algorithm

Simulated annealing falls into a category of optimization algorithms known as probabilistic methods, since there is some randomness involved in determining the path taken in search of the solution. A sequence of solutions are generated by randomly creating a new solution via a perturbation to the current solution and then accepting or rejecting the new point with a certain probability which is dependent on the temperature and the change in the objective function.

II.IMPLEMENTATION

One of the appealing features of the simulated annealing algorithm is its ease of implementation. The basic algorithm can be coded in only a few

```
x = Initial_State;
f = Cost(x);
T =  Initial_Temperature();
do   {
     do   {
          new_x = Apply_Perturbation_To(x);
          □f = Cost(new_x) - f;
          if ( (□f<0) OR (random[0,1]<exp(-□f/T)) ) { x = new_x;
               f = f + □f;
               }
```

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```
    } while Not_At_Equilibrium(); T =
    Update_Temperature(T);

} while Exit_Condition_Not_Met();
```

	4 Elements of Implementation	
1	Search Space	specified as part of the problem formulation
2	Objective or Cost Function	
3	Perturbation Mechanism	specified by as part of the solution algorithm
4	Cooling Schedule	

Table .2 Implementing Simulated Annealin

Total Real Power	**Initial**	**Final**	**Change**	**% Change**
input	1.6865 p.u.	1.6812 p.u.	-0.0053 p.u.	-0.314%
delivered	1.6620 p.u.	1.6620 p.u.		
loss	0.0245 p.u.	0.0192 p.u.	-0.0053 p.u.	-21.6%
% loss	1.455%	1.143%	-0.313%	-21.5%

III. CONCLUSIONS

The objective of this paper is to show that the simulated annealing algorithm can be used successfully to find the configuration of a three-phase power distribution network which minimizes the overall real power losses of the system. This work is to provide a basis for the development of algorithms and computer programs which could be included in the software used by power utility companies to make effective decisions regarding the configuration of their distribution networks.

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