A Multiagent System Approach and Integer Linear Programming for Transformers Relocation in Power Distribution System

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***Abstract*—This paper presents a study of the development of a Multiagent System for transformer placement according to its load. The growing demand for electricity requires a better management of distribution transformer load. Due to this problem many transformers are operating over their load limits. The replacement of an overloaded transformer by another of higher power is the normal procedure to solve the problem. The proposed model considers the replacement of an overloaded transformer by an under loaded and vice-versa. The Multiagent System was conceived to give a support for management activities of transformers replacement. The system also supplies economical information for the transformer replacement.**

I. Introduction

Operational planning of power distribution feeders requires a considered effort for operation and design of affected feeders. Studies for electrical grid planning require a high level of human intervention, as well as considerable time for their analysis. Grid planning is required due to the constant need for network expansion caused by the rapid growth of demand in urban, rural and public policies related to social inclusion. Normally, for analysis and study purposes, electrical power systems are subdivided into three large blocks, which are: generation, transmission and distribution [1]. Investments made in the distribution sector represent a significant percentage of the budgets of distribution utilities. The investments applied in the electricity distribution segment constitute a significant percentage of the budgets of the distribution concessionaires. Many factors indicate the importance of this part of the electrical system, including: Low voltage network is the part of the system responsible for customer service; it operates at a lower voltage level, having the largest concentration of consumers; the costs involved for the operation, construction and maintenance are too high. The high investment and operating costs, added to the fact that the distribution system is what connects directly to consumers provide highly important to the planning system expansion. Derived actions of the planning process can lead gains in substantial expansion and operating costs. In addition to financial gains, proper planning of the distribution network could allow consideration of issues such as power quality, network reliability, limitations on budgets and expansion possibilities. In this context, this paper presents a multiagent approach for supporting the relocation analysis of the overloaded transformers by under loaded ones and vice-versa. Among the benefits brought by a more adequate transformer management related to their load, the operational costs reduction (electrical losses), the optimization of the equipment lifetime, the improvement of circuit levels tension and the growth of the electrical network reliability and efficiency are highlighted.

II. Theoretical Foundation

A. Replacement of Transformer in Low Voltage Network

The relocation problem of distribution transformers consists of replacing transformers overloaded by under loaded transformers and vice versa. Considering an urban area, the number of combinations is high, being classified as a combinatorial optimization problem. The problem has a non-linear feature according to the values of losses in the iron and copper of the transformers. Generally the problem can be represented as a nonlinear mixed-integer programming model [2]. To solve this problem, classic methods such as quadratic and mixed integer programming are applied. However, in some cases, the methods may fail to reach the global maximum and only reaches the local maximum. The problem can be solved by using an evolutionary approach regardless of the type of the objective function [3]. Meta-heuristic methods as AG, Particle Swarm Optimization, Simulated Annealing or variations are commonly used in the solution of network planning problems [3].

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The main goals expected in the relocation of transformers are:

- Reduction of energy losses costs;
- Reduction of loss of life of the equipment;
- Circuit voltage level improvement;
- Increase in the electricity distribution system efficiency;
- Increase the reliability of the network.

Operating costs are comprised of two parts: the cost of the iron losses and the cost of copper losses. The investments needed to meet the relocation expenses, transportation, removal, material and administrative expenses. It is also considered the cost of interruption of electricity supply during installation and removal of the transformers. The normal procedure of replacing transformers corresponds to the replacement of transformers overloaded by higher power transformers.

B. Multiagent Systems

An agent is a software (or hardware), an entity that is situated in some environment and is able to autonomously react to changes in that environment [4]. In turn, the environment is everything external to the agent, and can be physical, such as the electrical system, or internal, such as a database. The agent can cause a change in the environment, through a physical action, requesting the closure or opening a piece of equipment, or virtual, as the information storage control in a database. The agent must maintain their independent thinking ability of the environment in which it is inserted. An intelligent agent must have the following features:

- Autonomy: agents should be operated without human intervention or other agents, and have control of their actions and internal state;
- Reactivity: an agent should be able to react to changes in their environment;
- Proactivity: agent behavior is the result of your goal, this characteristic refers to the agent's ability to take initiative;
- Social ability: agents are able to interact with other intelligent agents.

The multi-agent systems correspond to two or more agents or intelligent agents [5]. Agents can have the ability to communicate with each other, one key feature that differentiates the multi-agent systems of other types. Related to power transformers, in [6] one Multi-Agent System used for monitoring of equipment condition is presented. Coordination of protection in distribution systems is discussed in [7] where agents are used for fault detection on the network. The network reconfiguration is treated in [8], which proposes architecture to assist in reconfiguration of the network, where each agent works in a decentralized manner.

C. Integer Linear Programming

Operations research is a science that aims to provide quantitative tools to the decision-making process. The mathematical programming is a tool used by operations research in the process of obtaining quantitative models. Consists of techniques and algorithms that aims to solve the structure and quantitative models using a mathematical representation. The algorithms handle the representation of maximization or minimization problems of an objective function with consideration of restrictions that are imposed on the proposed model. Due to its wide applicability, the methods were specialized to solve particular cases. According to Goldbarg and Luna [9], the Linear Programming is a particular case of programming models in which the variables are continuous and have linear behavior, both in relation to restrictions and the objective function. A particular case of a discrete variable is one in which the variables assume only the values zero or one (0/1), are known as binary variables typically used in the decision making process. In this work we used an integer approach to determine the transformers to be moved.

III. Metodology

A. Problem Formulation

For the determination of acceptable transformers replacements on the network, the following criteria were considered:

- Under loaded Transformer: Maximum load not exceeding 65% of their nominal power;
- Overloaded transformer: Maximum load exceeding 150% of their nominal power;
- Maximum distance of 30 km between potential transformer changes.

The objective function was defined to minimize the voltage drop, losses and cable change operating costs, phase load balancing, capacitor e DG positioning and sizing. Each of these criteria characterizes a multicriteria problem which considers the minimization of the functions shown in the equation (1). The objective function was defined to minimize the cost of the iron losses, cost of copper losses, energy interruption costs and operational costs. Operational costs for each transformer represent the following tasks: installation, transportation, removal, administrative expenses and cost of materials. Each of these criteria characterizes a multicriteria problem which considers the minimization of the functions shown in the equation (1).

$$F.O. = min\,(f1 + f2 + f3 + f4) \tag{1}$$

where:

f1: Cost of iron losses;
f2: Cost of copper losses;
f3: Cost of energy interruption;
f4: Operational costs.

The determination of iron losses is shown in the equation (2).

$$min \sum_{k=1}^{j} \sum_{t=1}^{n} \left\{ C_{UPC_k} * P_{FE_k} * \frac{1}{(1+t)^t}) \right\} \quad (2)$$

Onde:

k: Index of the transformer;
j: Number of transformers on the analysis;
t: Year;
n: Number of years, if transformer is overloaded n =1, under loaded n =5;
C_{UPC_k}: Unity cost of constant losses for transformer k;
P_{FE_k}: Loss of nominal demand in iron for transformer k;
t: Minimum attractive rate of return = 12 %.

The determination of cooper losses is shown in the equation (3).

$$min \sum_{k=1}^{j} \sum_{t=1}^{n} \left\{ C_{UPV_k} * P_{CU_k} * f_u^2 * \frac{((1+g)^t)^2}{(1+t)^t}) \right\} \quad (3)$$

Onde:

k: Index of the transformer;
j: Number of transformers on the analysis;
t: Year;
n: Number of years, if transformer is overloaded n =1, under loaded n =5;
C_{UPV_k}: Unity cost of variable losses for transformer k;
P_{CU_k}: Loss of nominal demand in cooper for transformer k;
f_U: Utilization factor;
t: Minimum attractive rate of return = 12 %;
g: Growth rate = 6 %.

The cost of interruption considers all the customers supplied by each selected transformer for exchange multiplied by an average rate. The transportation cost considers the distance multiplied by the value specified in table 1 according to the power of the transformer. The operational costs are shown in table I.

TABLE I
OPERATIONAL COSTS

Replacement (kVA)		Transportation (R$)	Removal , administrative expenses and materials (R$)
35	45	200	2000
45	75	215	2500
75	112,5	230	3000

B. Modelling Transformers as Agents

The characteristic of communication between agents was fundamental for modeling the system, each transformer was modeled as an agent. The agent transformer contains the value of supplied load, nominal power, coordinates of placement, and amount of consumers. The approach used in this study allows the transformers may change position without the need for replacement in pairs. Thus, the objective is to analyze a wider range of exchange opportunities between the transformers. The agents were inserted into the solution with a unique identifier, providing the basis for the location of the agent for the exchange of messages. Due to the modeling analysis, a class of agents called Transformer was created. The amount of agents of type Transformer may vary according to each study to be performed. The main purpose of the agent Transformer is to negotiate with other agents the possibility of position exchange in the network, in such a way that an under loaded transformer can be replaced by an overloaded and vice versa. In the initialization of each Transformer agent its load is calculated and identified if the transformer is overloaded or under loaded. The messaging process is initially made among the Transformer agents. Therefore, each agent can set a list of desirable moves according to the initial request. In order to make the validation of the solution an agent called Supervisor was designed. The Supervisor agent has an overview of the distribution of transformers and has additional restrictions, such as operational cost and amount of maintenance teams available. The Supervisor agent receives the list of possible coalitions of each Transformer agent, determining which are possible to perform. After the consistency of solutions, calculates the cost of each association and defines an execution priority list. The process of exchanging messages between the Transformers agents obeys the following sequence:

1) Each Transformer is initialized and determined its load, power and positioning;
2) Each Transformer query agents created in the study;
3) Each Transformer sends a message to the recovered agents, requesting to inform its power and coordinates;
4) Each Transformer receives the request and responds to the requested agent its power and coordinates;
5) Each Transformer receives the message and calculates if the sender can be inserted in your list of coalitions;
6) Each Transformer after receiving messages from all agents, sends your list of coalitions for the Supervisor;
7) The Supervisor, based on lists of coalitions of the Transformer, formulates a mathematical model to run;
8) Each Transformer, waits for the supervisor's response to the agent suggested to its coalition, when exist.

The process of exchanging messages between the agents Supervisor and Transformer occurs as the following:

1) The Supervisor controls the receipt of the message of each Transformer informing their load values, power, positioning and a list of coalitions;
2) The Supervisor query inconsistencies in the lists of coalitions of all Transformers;
3) The Supervisor calculates the total costs involved in each suggested coalition;
4) The Supervisor elaborates a mathematical formulation with the associated costs of all coalitions;
5) The mathematical model is executed and the Supervisor defines coalitions according to the model result.

The sequence diagram for negotiation between three Transformers and subsequently the passage of the coalition list for the Supervisor can be visualized as shown in Figure 1.

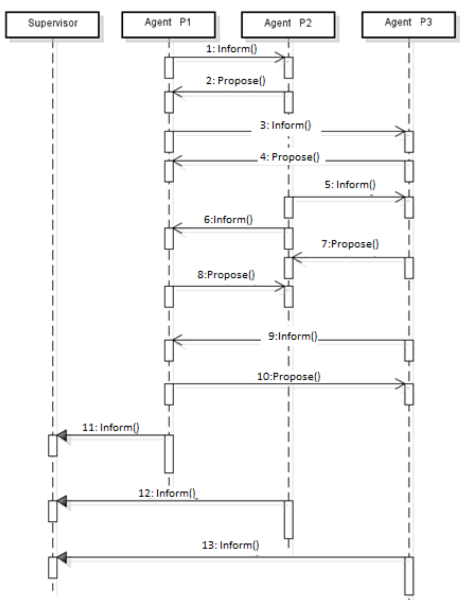

Fig. 1. Simulation results for the network.

Coalitions specified for each Transformer agent list is handled by the Supervisor as a directed graph. A graph is defined by an ordered pair of sets (V, E) such that the graph V is finite, and each element of a subset is formed by two elements of V. Each element of V is called a vertex and E is called edge of the graph. In a directed graph edges have meaning and form a multiset. In this modeling each vertex is represented by a Transformer agent and the edges correspond to the coalitions that can be performed. Figure 2 illustrates a situation that Transformer agent (P1) may change place with Transformer agent (P2) as well with Transformer agent (P3). However, (P1) and (P3) combination cannot be made. This is due to the fact that the (P1) can assume the load of (P3), but (P3) does not have enough power to assume the consumers of (P1).

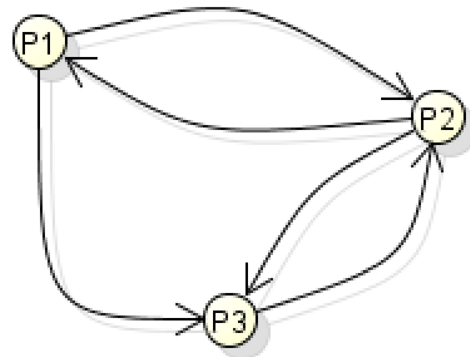

Fig. 2. Grafo dirigido.

In this case the graph represented by figure 2 can be defined by the equations (4), (5) e (6).

$$G = (V, E) \tag{4}$$

$$V = \{P1, P2, P3\} \tag{5}$$

$$E = \{\{P1, P2\}, \{P1, P3\}, \{P1, P2\}, \{P2, P3\}, \{P3, P2\}\} \tag{6}$$

The Supervisor agent must validate the resulting graph of the lists of possible coalitions of Transformer agents and generate the corresponding mathematical formulation. The Transformer agents help in reducing the solution search space, moving to the Supervisor agent only valid reallocations.

C. Integer Linear Programming Model

The formulation refers to a problem in the context of traditional network optimization flow. The edges represent the possible connections of the transformers with their cost. In the graph vertices are conservative obeying the First Law of Kirchhoff [9]. This feature is important because it ensures that each vertex always have an associated transformer, avoiding solutions that can assume that a node in the network is assigned without a transformer.

The objective function can be shown in equation (7).

$$min \left\{ \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} * Troca_{ij} + \sum_{j=1}^{n} \sum_{i=1}^{n} C_{ji} * Troca_{ji} \right\} \tag{7}$$

where:

i: Index of the transformer;
j: Index of the transformer;

TABLE II
TRANSFORMERS CONDITIONS

Identify	Power (kVA)	Load (kVA)	Use (%)
P1	45	80	177
P2	40	112,5	36
P3	45	60	133
P4	75	50	67

n: Number of transformers on the analysis;
C_{ij}: Unitary cost of changing transformer type i to type j;
$Troca_{ij}$: Binary variable indicating change of the transformer type i to j;
C_{ji}: Unitary costs of changing transformer type j pelo i;
$Troca_{ji}$: Binary variable indicating change of the transformer type j pelo i.

The constraints are shown in equation (8) and (9).

$$\sum_{i=1}^{n}\sum_{j=1}^{n} Troca_{ij} = n \quad (8)$$

$$\sum_{j=1}^{n}\sum_{i=1}^{n} Troca_{ji} = n \quad (9)$$

The constraints represented by the equations (8) and (9) ensure that, with the execution of the transactions, each point will have an associated transformer.

Where:

i: Index of the transformer;
j: Index of the transformer;
n: Number of transformers on the analysis;
C_{ij}: Unitary cost of changing transformer type i to j;
C_{ji}: Unitary cost of changing transformer type j to i;

IV. RESULTS

The proposed model of the agents was coded in Java programming language using the JADE framework. The mathematical model was developed to run on free solver GNU LP / MILP Solver Kit (GLPK). The studies deal with real transformers, whose data were obtained directly from the database of Companhia Paranaense de Energia (COPEL).

The present study illustrates the execution of the multiagent system in a network with 3 transformers. The circuits of the data are shown in table II.

Coalitions returned by each Transformer agent can be shown in table III.

The initial list of coalitions defined by the Transformers agents for the Supervisor can be represented by the graph shown in figure 3.

TABLE III
LIST OF COALITIONS

Identify	List of coalitions
P1	{(P1,P2), (P1,P4)}
P2	{(P2, P1), (P2, P3), (P2, P4)}
P3	{(P3, P2), (P3,P4)}
P4	{(P4, P1), (P4, P2), (P4, P3)}

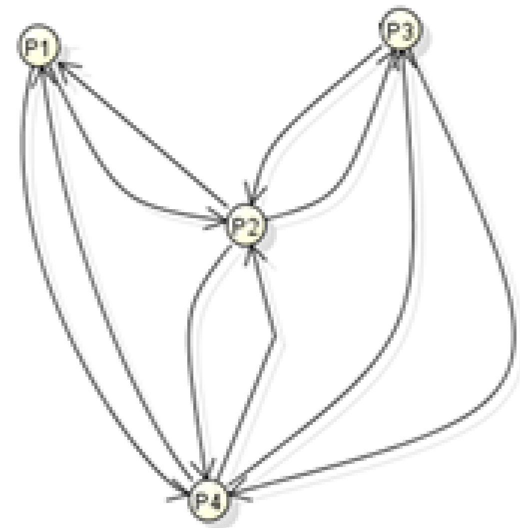

Fig. 3. Initial graph.

The values calculated by the Supervisor for each edge are shown in table IV.

TABLE IV
COALITION COSTS

Coalitions	Cost (R$)
P1	{(P1,P2), (P1,P4)}
P2	{(P2, P1), (P2, P3), (P2, P4)}
P3	{(P3, P2), (P3,P4)}
P4	{(P4, P1), (P4, P2), (P4, P3)}

According to the suggested coalitions by each Transformer agent, the Supervisor elaborates the mathematical model to be processed. The result of the process is represented in table V.

TABLE V
SUGGESTED CHANGES

Change	Cost (R$)
P1 P2	12.700
P2 P1	12.700
P3 P4	12.700
P4 P3	12.700

V. CONCLUSIONS

This paper presented a methodology based on multiagent systems to support relocation of transformers in a low voltage distribution network. Transformers agents were modeled to elaborate possible coalitions indicating a preferred list of transformers to perform relocate.

After determining the list of probable relocations, the Supervisor agent with a global visibility of all transformers, elaborates a graph to perform an integer linear programming-based design and performs the call to the solver GLPK. The initial lists of the Transformers agents are used by the Supervisor agent to limit the search space of the solution.

The existence of a Supervisor allows additional restrictions can be incorporated in the system, affecting the initial coalition realized by the Transformers agents.

The optimal combination was obtained, the Supervisor agent has an important role in the system, providing additional validation and constraints that the Transformers agents don not have access. This work contributes to analyze the impact of the insertion of multiagent system to contribute to operational planning of a distribution electrical network. To achieve this goal, agents communicate, cooperate and negotiate to determine their actions.

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