Development of Distributed Control System for Load Distribution Among Transformer Substations Based on Thom's Catastrophe Theory

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Abstract: The income from the transformer exploitation increases with the energy transformed by. However, the overload causes exponential decrease of transformer lifetime. Fortunately, sometimes the interconnection topology of 22 kV network permits the redistribution of load between different transformers. The goal of load-redistribution is to reach the maximum income within the lifetime of transformer. To reach the optimum, the temperature of transformer must be computed, and then the lifetime decrements must be evaluated. The optimal distribution is solved by switching outgoing distribution lines between different buses. The application of Thom's catastrophe theory gives opportunity to make a real-time load distribution among transformers.

Keywords: catastrophe theory, lifetime decrement, load distribution, neuro-fuzzy control

1 Introduction

Nowadays the market of electric industry in Israel is going toward to fast changes. In the next few years the economic environment of IEC will be changed. Different financial conditions mean different economical optimum for planning and operation transformers. The goal is to find the golden track between the long term (from 5 to 15 years) planning and operational optimum although taking into consideration the fast changing monetary situation. The optimal load distribution between substation transformers is a function of economic rules in addition to the technical limits.

The control system requires a techno-economic model for optimal planning and operation of substation transformers. The model has to take into consideration the following inputs:

- Measurements originated from he IEC's SCADA system,
- Interconnection topology of 22 kV network and substation transformers.

Components of techno-economic model are the following ones:

- Incomes from energy distribution,
- Amortization costs,
- Lifetime shortening because of overheating,
- Efficiency decrease because of overload,
- Penalty cost of load limitation.

The following tasks has to be done:

- Identifying the feasibly parameter ranges in the model,
- Analyzing the model with the help of Thom's catastrophe theory to find the parameter values of critical points,
- Creating fuzzy rules for optimal load distribution,
- Modifying the SPSS Clementine's Artificial Neural Network for our model's purpose,
- Performing simulations that will be the basis of load distribution development strategies.

2 Principle of Operation

The catastrophe theory developed by René Thom is a useful method for analyzing large-scale systems. This method enables to solve the main problem of real-time controlled extremely slow processes. In extremely low speed processes, the perception of changes is a hard task. Although the computational speed is high enough, the determination of critical points is complicated because of the low speed of change. Thom's catastrophe theory can be used to discover the critical points without complicated and long-time computation.

Temperature of trasnsformers is changing slowly related to the changing of consumer load. Therefore warming up of transformer is delayed but affects on the statement of transformer and it occurs lifetime decrement. Measure of lifetime decrement depends on the previous consumer load and the temporary consumer load which warm the transformer up.

Warming up the transformer might occur either lifetime decrement while the capability is hold about the nominal value or capability decrement for the full lifetime.

In the first case the lifetime of transformer is shorter, duration for producing income is shorter and to reach a suitable profit requires higher specific price from the consumers but the planned income can be reached faster. Then investment for new transformer has been required sooner.

The second case results the transformer is operating during full lifetime but the income will be growing slower and to reach a suitable profit requires lower specific price.

The income from the transformer exploitation increases with the energy transformed by. However, the overload causes exponential decrease of transformer lifetime. Fortunately, sometimes the interconnection topology of 22 kV network permits the redistribution of load between different transformers. The goal of load-redistribution is to reach the maximum income within the lifetime of transformer. To reach the optimum the temperature of transformer must be computed, and then the lifetime decrements must be evaluated.

The optimal distribution is solved by switching outgoing distribution lines between different buses. The action of switching will be performed according to a set of considerations rather than in constant prefixed point. These considerations lead to a set of possible switching point, more accurate, to the range or ranges of switching. There is quit possible that one or more sub ranges have bifurcation points or zones.

3 Temperature of Transformers

The temperature of the transformer depends on its load and the technical features. According to J. C. Martin's hand book (Martin, 1969)

The heating function is:

$$\vartheta = \hat{\vartheta}(1 - e^{-\tau/T}) \tag{1}$$

The cooling function is:

$$\vartheta = \hat{\vartheta}(e^{-\tau/T}) \tag{2}$$

where

ϑ [°C] is the temperature difference between the transformer body and the environment, $\boldsymbol{\tau}$[sec] is the sample time when the temporary load has been measured, and T [sec] is the thermal time constant of transformer computed by

$$T = \frac{cG}{K_d S_d} \tag{3}$$

where K_d $[\frac{W}{m^2 C}]$ is the heat transfer coefficient, S_d $[m^2]$ is the heat transfer surface of transformer, *c* [kJ/°C/kg] means the heat capacity, *G*[kg] is the mass of transformer.

Final temperature of the process computed by the following equation:

$$\hat{\vartheta} = \frac{\Delta P}{K_d S_d} \tag{4}$$

where ΔP [W] is the transformer total loss (load dependant), computed by

$$\Delta P = \Delta P_0 + \Delta P_{CU_n} \frac{I_L^2}{I_n^2} \tag{5}$$

In the other words, $\hat{\vartheta}$ depends on the load current, according to:

$$\hat{\vartheta}(I) = \frac{1}{K_d S_d}(\Delta P_0 + \Delta P_{CU_n} \frac{I_L^2}{I_n^2}) = C_1 + C_2 I^2 \tag{6}$$

4 Current Load on Transformers

The maximum current permitted on j^{th} transformer at the permitted temperature can be expressed from the previous equation which value means the maximum of current load belonged to the maximum temperature $\hat{\vartheta}(I = I_{j,\max})$ of transformer:

$$I_{j,\max} = \sqrt{\frac{\hat{\vartheta}(I_{j,\max}) - C_1}{C_2}} . \tag{7}$$

Let $I_j(\tau)$ be the temporary current load measured on j^{th} transformer in time τ, and $I_{j,max}$ means the temporary nominal value of current load which depends on used lifetime. Then the membership function μ_I computed for $I_j(\tau)$ is

$$\mu_I = \{I; I_j(\tau), I_{j,\max}\} = \{P; P_{meas}, P_{temp}\} . \tag{8}$$

There is an other fuzzy set which includes values of temperature of transformer. The membership function for the temporary value of temperature is computed by the following equation.

$$\mu_{\vartheta} = \left\{ \vartheta; \vartheta_0, \hat{\vartheta} \right\}, \tag{9}$$

where $\hat{\vartheta}$ is the maximum temperature which depends on used lifetime, and it is permitted on the j^{th} transformer temporarily, and ϑ_0 is the environmental temperature.

The current belonged to temperature $\hat{\vartheta}$ is $I_{j,max}$ expressed previously. Then the maximum power load for the j^{th} transformer on the maximum of temperature is

$$P_{temp} = \sqrt{3} \cdot I_{j,\max} \cdot U_1, \tag{10}$$

and the measured consumer power load on the j^{th} transformer is

$$P_{meas} = \sqrt{3} \cdot I(\tau) \cdot U_1, \tag{11}$$

where $U_1=161kV$ is the primary voltage, $I(\tau)$ is the measured consumer current in time τ.

The power load on the j^{th} transformer has to be checked if load distribution is required or not. The computational process is the following: if the measured current $I(\tau)$ is higher than the current $I_{j,max}$ computed from the permitted temperature of transformer then $k_1=1$ and $k_2=0$, else $k_1=0$ and $k_2=1$.

The distribution of power load among the current bus connected parallel and the j^{th} transformer can be computed by the following equations which are transfer functions of neuro-fuzzy system.

Power load on the j^{th} transformer is

$$P_j(\tau) = k_2 \cdot P_{temp} \cdot \mu_I + k_1 \cdot P_{nom} \cdot \mu_{\vartheta}. \tag{12}$$

Separated part of power load on the j^{th} transformer which has to be switched over the connected bus is

$$P_{bus}(\tau) = k_1 \cdot \left[P_{temp} \cdot (1-\mu_I) + P_{nom} \cdot (1-\mu_{\vartheta}) \right]. \tag{13}$$

The total power load on connected bus will be the sum of power load $P_{bus}(\tau)$ separated from the power load on j^{th} transformer and temporary power load on connected bus. It seems the rate of distribution depends on the temporary consumer load, and the permitted temperature for j^{th} transformer, and the used lifetime of j^{th} transformer.

The function of power load distribution can be seen in Figure 1. Those curves show the power load is distributed among the j^{th} transformer and the connected bus, on a specific temperature.

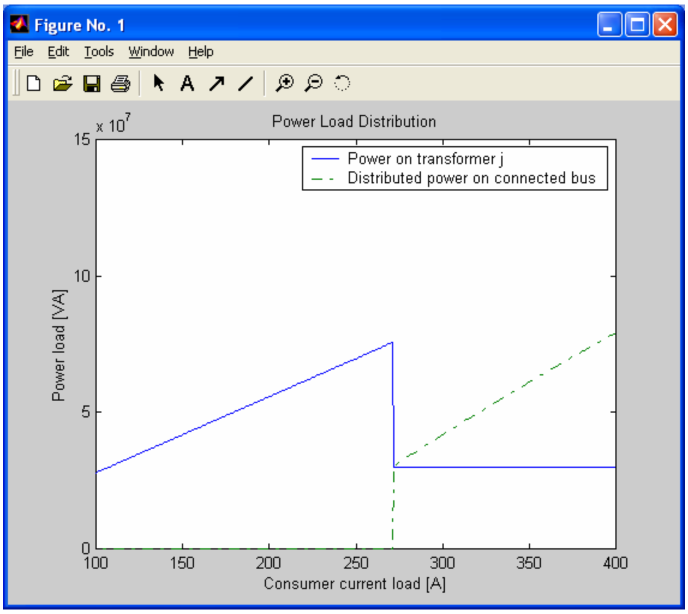

Figure 1
Power load distribution

The changing of rate of load distribution depended on temperature of transformer, the consumer load and the used lifetime of transformer is shown in the Figure 2. It seems when value of the power load has reached the limited value then the power load distribution will change.

The distribution occurs the power load reamined on the j^{th} transformer will be set on a constant value, and the power load switched over the connected current bus will be changing in accordance with the changing of consumer load.

The value of distributed load on j^{th} transformer will be set in accordance to the maximum temperature and the used lifetime. If the permitted temperature of transformer has been decremented the power load remained on transformer after distribution will be also decremented shown in Figure 2.

The levels of distributed power load on transformer can be seen in this figure. The higher power level means higher permitted temperature on transformer. It seems the power load on connected current bus is also leveled and the sum of two quantities, the power load on transformer and power load on connected current bus, give the total consumer power load. The function is a four-dimensional expression, where the fourth dimension is the temperature of transformer and this dimension is shown as levels of power load.

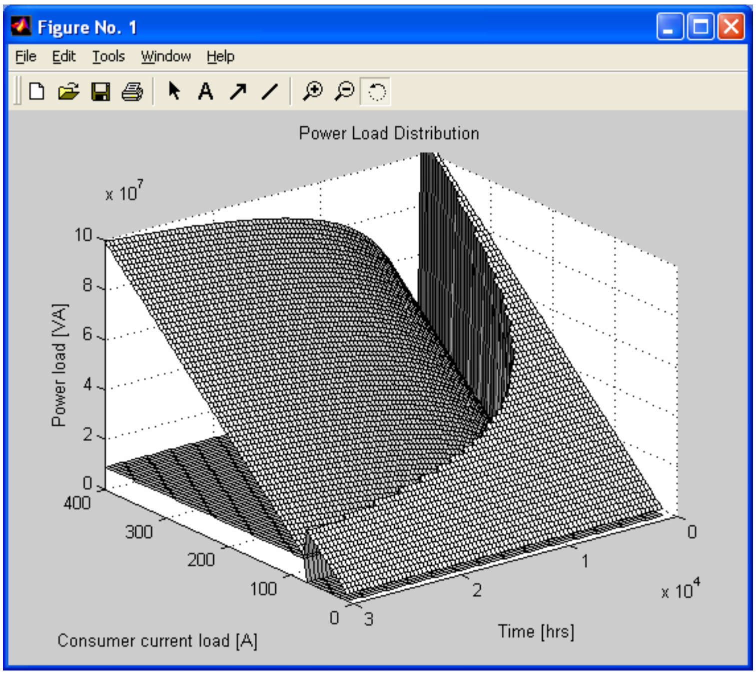

Figure 2
Function of power load distribution

In this case, the power load is tuned by setting the permitted temperature of transformer. The level of power load on transformer may be higher when the permitted temperature is higher.

Increasing of operational time and warming up occur the decrement of capability of transformer. Decrementing the power load requires load distribution. Figure shows that changing of loading can result a jump in power load, when the power load on transformer will drop on a lower constant value and the power load on connected bus will be rising.

Current bus load is composed from the sum of temporary load on bus connected to the $(j+1)^{th}$ transformer and a separated part of power load on j^{th} transformer. This function is a four-dimensional expression, where the fourth dimension is the temperature of transformer. Fourth dimension is shown as level of power load remained on j^{th} transformer and bus of $(j+1)^{th}$ transformer.

Value of loading and value of lifetime decide when such an event is occurred. Since these parameters set the working point on an other level suddenly, the event is catastrophe event, a switching catastrophe. The switching level can be changed. In this case switching parameters for setting levels are the permitted temperature and the used lifetime.

5 Control of Load Distribution inside a Substation

The goal of control is to reach the maximum profit and the possible maximum of lifetime of transformers. This goal requires suitable control process to realize an optimum relationship among the lifetime, and the maximum income from maximum of consumer load.

Since the load is changing slowly, the gradients of overload functions and value of overheating are small. There is not a well defined switching point for load redistribution! The supervision of working points and the switching is a hard task under these conditions. Efficient control requires well-defined switching value.

Switching range can be calculated by the application of catastrophe theory, the switching catastrophe, rather than switching point The most important difference between the switching catastrophe and the elementary catastrophes is that there is a gradient typed bifurcation. It is necessary because of the small gradient of function which describes the process being either too fast, or too slow.

The load distribution is controlled in according with the used lifetime of the j^{th} transformer. The switching level determines when the load distribution has to be set on or off. The switching level is changing exponentially with the lifetime and the temperature of transformer occurred by the loading as it is shown in Figure 3.

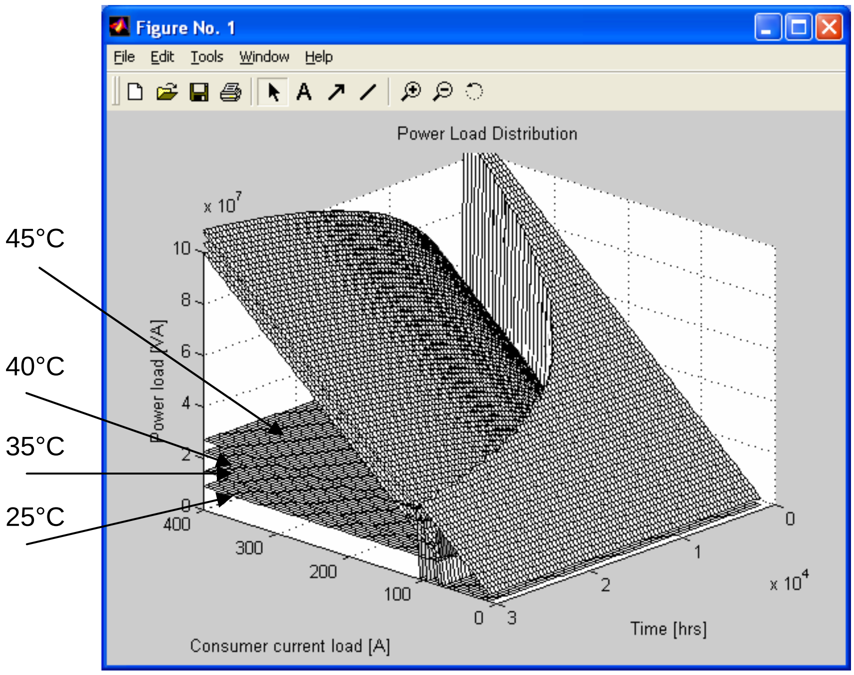

Figure 3

Load distribution among transformer j and the connected bus

When the power load reached the switching level then the loading on j^{th} transformer is interrupted and the loading of transformer will set on a lower lavel while the distributed part of power load on j^{th} transformer will be added to the temporary loading on bus of another transformer. Changing of power load on bus is exponential function by the lifetime and the temperature of j^{th} transformer.

Input of control system is the measured value of temporary power load for computing the rate of load disribution by switching coefficients k_1 and k_2 and μ_ϑ and μ_I. The scheme of control is shown in Figure 4.

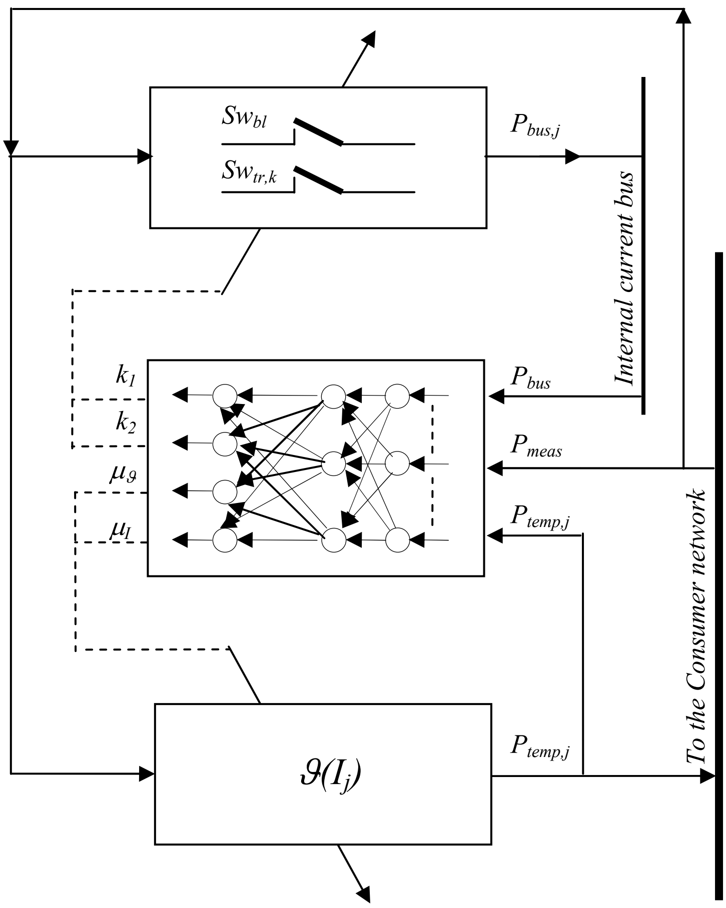

Figure 4
Scheme of power load distribution control

6 Neuro-Fuzzy Network for Load Distribution among Substations

Substations connected into network requires continuous observation of consumer load. The distribution is realized by the setting of quantity of consumer load in accordance with the permitted capabilities of all single substations which depends on the age and condition of transformers inside the substation.

The goal of application is to be able control chaotic changes of consumer load. Chaos is occurred by uncontrollable (or random) changes of the consumer current load. The consumer load may be featured by a trend of growth, a static statement, and a trend of reducing. But the start-in-time of any trends are not defined, and there may be more unespected changes during any session of consumer load.

The scheme of load distribution among transformer substtions can be seen in Figure 5, where N^2CTSk means the k^{th} transformer substation, $P_{temp,k}$ the permitted power load in the k^{th} transformer substation.

The energy input cőmes along the power station network, and the distributed power will be connected on the consumer network. The power required by consumers is measured in the consumer network and is divided among the transformer substations. The central neural network determines the rate of distribution among the transformaer substations. The rate of distribution m_k depends on the temporarily permitted power load of transformer station which is computed from the age of transformers being in the k^{th} transformer substation, where the age of transformer defines the permitted current load on transformer shown in Figure 2. The power load distribution inside transformer substations is controlled in accordance with scheme shown in Figure 4.

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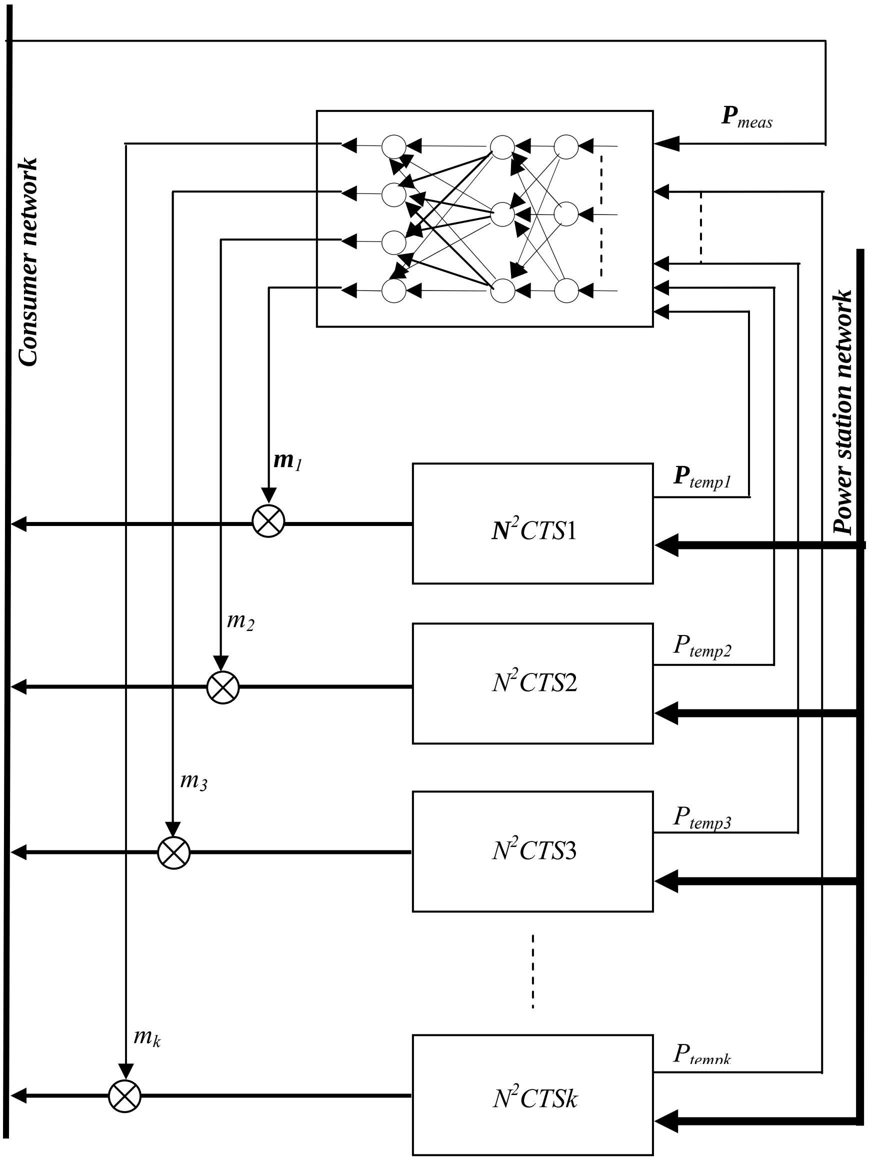

Figure 5
Distributed neuiral network control for load distribution

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