Dynamic Modeling and Simulation of Power Transformer Maintenance Costs

Olga Ristić[1], Bratislav D. Iričanin[2], Vladica Mijailović[1]

Abstract: The paper presents the dynamic model of maintenance costs of the power transformer functional components. Reliability is modeled combining the exponential and Weibull's distribution. The simulation was performed with the aim of corrective maintenance and installation of the continuous monitoring system of the most critical components. Simulation Dynamic System (SDS) method and VENSIM PLE software was used to simulate the cost. In this way, significant savings in maintenance costs will be achieved with a small initial investment.

Keywords: Modeling, Exponential and Weibull's distribution, Simulation, Power transformer, Maintenance.

1   Introduction

Power transformers are one of the most important and critical components in the electric power distribution system. It is significant to determine the maintenance costs of power transformer and prevent the failure beforehand by applying preventive maintenance activities [1].

Dynamic modelling of power transformer maintenance activities based on different strategies of maintenance, determining the optimum moment of replacement elements, the spare parts purches time, as well as minimizing the costs incurred in carrying out maintenance activities. Equipment behaviour is crucial for the implementation of preventive maintenance activities. In the dynamic modelling of power transformer reliability is necessary to establish a plan under which it shall be based on events and changes in the system, monitoring the state of certain elements, to determine the probability of component some failure generation.

For equipment that is being utilized for many years, modeling sets the minimum maintenance costs as well as interruptions in the supply of electrical energy (EE) to final consumers, according to [2, 3]. By analyzing the corrective

---

[1]Faculty of Technical Sciences Čačak, University of Kragujevac, Svetog Save 65, 32000 Čačak, Serbia;
 E-mails: olga.ristic@ftn.kg.ac.rs; vladica.mijailovic@ftn.kg.ac.rs
[2]Faculty of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11000 Belgrade,
 Serbia; E-mails: iricanin@etf.rs; iricanin@ftn.kg.ac.rs

maintenance strategies and continuous monitoring system instalation (CSMI) of critical elements in the example of a power transformer, it will be determined by combining the activities that aim to minimize costs and maximize power transformer availability [4].

In the recent years, for different types of calculation simulation that occure by numerical evaluation of model by the implementation of various software. The simulation can be used to predict system behaviour and optimization. In the paper will be apply the SDS method to simulate power transformer maintenance costs.

2   Model Development for Power Transformer Maintenance Activities

Failures that occur on the equipment in the most cases result deficits or interruptions in the delivery of EE to final consumers. The losses at the distribution company is proportional to the degree of equipment damage and to the cost of undelivered EE quantity. Consumer losses depending on the length and structure of the interruption of EE consumption. Failures that occur on power transformers cause the most serious consequences because their removal takes time and costs. Therefore, right on their availability is an important technical and economic issue [5].

Failures can be repairable (avoidable) and unreparable (unavoidable). Elimination of power transformer avoidable failures takes a relatively short time and does not require spare parts. In order to remove unreparable failures spare parts ought to be used, so that the duration of failure elimination depends on their availability. Purchase of spare elements significantly influences the duration of the failure when it occurs, but this purchase requires substantial additional investments [6].

Power transformer has six functional components: windings and oil, core, bushings, tank, on-load tap-changer and other accessories. It can be in the operating or failure condition. Failure condition of power transformer conversion can be divided into minor failures and major failures, which occur due to the loss of one or more of transformer functionality. Failures which can be removed for a period shorter than one day belong to minor failures.

Probability that component "k" of power transformer is in operating state is presented through the combination of exponential and *Weibull* distribution [7]:

$$R_k(t) = \exp\left(-(\lambda_{k,mf} + \lambda_{k,MF})t\right)\exp\left(-\left(\frac{t}{\alpha_k}\right)^{\beta_k}\right),\qquad(1)$$

where:

- t - time,
- α_k, β_k - Weibull scale and shape parameter for component $"k"$, respectively,
- $\lambda_{k,MF}$ and $\lambda_{k,mf}$ are major and minor failure rate of component $"k"$, respectively.

According to the expected duration of failure renewal time, there are three categories of failures [8]:

- failures which can be repaired for $t \leq 1$ day,
- failures which can be repaired for $1 < t \leq 30$ days,
- failures that can be repaired for $t > 30$ days.

The maintaining activities of power transformer may be considered depending on the implemented measures [7, 8] and can be carried out through:

1) corrective maintenance,
2) one-day maintenance,
3) oil regeneration,
4) insulation system regeneration,
5) power transformer refurbishment,
6) CMSI,
7) spare equipment optimization.

At this point, we shall consider only the case of extreme values of costs. More specifically, these are the costs of corrective maintenance and installation of continuous monitoring system (CMS) on power transformer elements.

2.1 Cost estimation model for corrective maintenance

The corrective maintenance is carried out in the case of operation without spare equipment or maintenance. In the planning period of exploitation costs, only the renewal costs will be included. During the period $(t, t+1)$ estimated annual value of these costs per transformer, can be calculate from the expression [7]:

$$C_{PT,b}(t,t+1) = \frac{\left[R_{tot}(t) - R_{tot}(t+1)\right] \sum_{k=1}^{b} p_k \left(\sum_{i=1}^{f_k} p_{k,i} C'_{k,i} \right)}{\int_{t}^{t+1} R_{tot}(t)\,\mathrm{d}t + \left[R_{tot}(t) - R_{tot}(t+1)\right] \sum_{k=1}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i}},$$

$$R_{tot}(t) = \prod_{k=1}^{b} R_k(t), \tag{2}$$

where:

- $C'_{k,i}$ - renewal cost of class "i" failure on component "k" if spare component "k" is not available,

- R_{tot} - reliability function of power transformer,

- R_k - reliability function of power transformer component ,

- p_k - probability that the failures occurs on power transformer component "k",

- f_k - number of failure classes of power transformer component"k", regard to the failure repair time,

- $p_{k,i}$ - probability that the failure of category "i" show in component "k",

- $r'_{k,i}$ - renewal time of category "i" occurs of component "k" if spare component "k" is not available,

- $r''_{k,i}$ - renewal time of category "i" occurs of component "k" if spare component "k" is available,

- b - number of functional components of power transformer.

2.2 CMSI cost model

The expected service life of the commercially available CMS is 10 years, and the purchase price is about 10% of the corresponding components purchase price. In the literature, the price and duration of detected faults mostly are ignored, because it is minimal or zero. For safety reasons, it is assumed that the detected defects in the windings and core eliminated in 5 days at a price of 5000 EUR, while on the other components will be eliminated only minor failures. By CMSI of power transformer components enables detection of failures at the earliest stage of development. This increases the intensity of minor and reduces the intensity of major component failures. Reducing the intensity of major failures has resulted in an increase in scale parameter of Weibull's distribution.

If we denote with α'_k, $k = \overline{1,2}$, scale parameter of winding and core after CMSI, CMS will be installing after T_S year of exploitation without failure.

If transformer will not fail for next 10 years of exploitation reliability will be change according to expression

$$R'_{tot}(t) \approx R_1(T_S) R_2(T_S) R'_1 (t-T_S) R'_2 (t-T_S) \prod_{k=3}^{b} R_k(t), \tag{3}$$

$$R'_k \left(t-T_S\right) = \exp\left[-\left(\lambda'_{k,MF} + \lambda'_{k,mf}\right)\left(t-T_S\right)\right]\exp\left[-\left(\frac{t-T_S}{\alpha'_k}\right)^{\beta_k}\right], \quad k = \overline{1,2}.$$

Expected costs in the first year after first CMSI are calculated as:

$$C_{PT,CMS}\left(T_s, T_s + 1\right) = \frac{X\left(\sum_{j=1}^{2} p_j \sum_{i=1}^{f_j} p_{j,i}^{CMS} C_{j,i}^{CMS-b} + \sum_{k=3}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} C'_{k,i}\right)}{\mathrm{Im}_{CMS}\left(T_s, T_s + 1\right)} +$$

$$+ \frac{R_{tot}\left(T_s\right) C_{s,1-2}}{Y\left(\sum_{j=1}^{2} p_j \sum_{i=1}^{f_j} p_{j,i}^{CMS} r_{j,i}^{CMS-b} + \sum_{k=3}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i}\right)} + C_{m-CMS},$$

$$X = \left(R'_{tot}\left(T_s\right) - R'_{tot}\left(T_s + 1\right)\right), \quad Y = \int_{T_s}^{T_s+10} R'_{tot}(t)dt + \left(R'_{tot}\left(T_s\right) - R'_{tot}\left(T_s + 10\right)\right),$$

$$\mathrm{Im}_{CMS}\left(T_s, T_s + 1\right) = \int_{T_s}^{T_s+1} R'_{tot}(t)dt + \left(R'_{tot}\left(T_s\right) - R'_{tot}\left(T_s + 1\right)\right) \cdot$$

$$\cdot \left(\sum_{j=1}^{2} p_j \sum_{i=1}^{f_j} p_{j,i}^{CMS} r_{j,i}^{CMS-b} + \sum_{k=3}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i}\right),$$

(4)

where:

- $C_{k,i}^{CMS-b}$ - renewal cost of category "i" on component "k" of power transformer if CMS is installed and component "k" is not available,
- $r_{k,i}^{CMS-b}$ - renewal time of category "i" on component "k" of power transformer if CMS is installed and component "k" is not available,
- $p_{k,i}^{CMS}$ - probability that the failure of class "i" occurs on power transformer component "k" after installing CMS,
- C_{m-CMS} - annual maintenance cost of CMS.

3 Power Transformer Cost and Failure Data Analysis

The CMSI will certainly decrease maintenance costs. In recent years, with the development of different types of sensors and information technology, it is possible to reduce preventive maintenance activities. If any changes in the equipment occurrence, it will provide data that indicate the need for preventive interventions. Therefore, it is considered to be the optimal time for installing CMS at every critical element of the power transformer, and then the costs would be minimal [9, 10].

In **Table 1** the data of component contribution in total number of failures of power transformers are given, as well as the duration of certain failures categories elimination. The values of the degree of detected faults are listed in **Table 2**. In the same table is the purchase price of components and power transformer 110kV, 110/x kV/kV, 31,5MVA.

Table 1 *Power transformer component reliability data and removal duration of certain categories failures [7].*

Component	p_k , %	Failure "category" by duration	$p_{k,i}$, %	$r'_{k,i}$	$r''_{k,i}$
1) Windings + oil	26,4	≤ 30 days	14,54	30	15
		> 30 days	85,46	250	15
2) Core	2,4	1÷30 days	50,00	30	15
		> 30 days	50,00	180	15
3) Bushing	12,0	≤ 1 day	14,82	1	1
		1÷30 days	51,85	40	3
		> 30 days	33,33	40	15
4) Tank	7,9	≤ 1 day	58,82	1	1
		1÷30 days	23,53	3	3
		> 30 days	17,65	90	15
5) On-load tap-changer	40,7	≤ 1 day	25,61	1	1
		1÷30 days	52,44	3	3
		> 30 days	21,95	40	3
6) Other accessories	10,6	≤ 1 day	65,22	1	1
		1÷30 days	17,39	15	15
		> 30 days	17,39	40	15

It is adopted that the price of undelivered EE $C_{PT} = 0,10$ EUR/kWh , time of refurbishment $t_{ref} = 28$ days, price of filtration and drying oil $C_{oil-fd} = 0,2 C_{new,oil}$, price of one-day maintenance $C_{one-day} = 100$ EUR , cost of oil regeneration $C_{reg.-oil} = 8000$ EUR , price of insulation regeneration $C_{reg.-ins} = 100000$ EUR , probability of reduction "technical age" of paper isolation $x = 0,3$.

Purchasing cost of CMS is 10% of component price on which CMS will be installing: $C_{s,k} = 0,1 C_{new,k}$. Annual maintenance cost of CMS is 1% of

purchasing price. In **Table 3** are presented the prices of failure renewal cost on power transformer components.

Table 2

Values for detection rate and price of new elements of power transformer 110/x kV/kV.

Component	The level of detection $d_k\,[\%]$	Cost of purchase new component $C_{new,k}\,[\text{EUR}]$
Windings + oil	70	250 000+ 40 000
Core	70	80 000
Bushing	80	800
Tank	-	28 000
On-load tap-changer	75	42 000
Other accessories	100	22 000

Table 3

Failures renewal costs for power transformer components

Component	p_k , %	Failure "category" by duration	Failure renewal cost without spares $C'_{k,i}$	Failure renewal cost with available spares $C''_{k,i}$
1) Windings + oil	26,4	≤ 30 days	$0,2C_{new,1}+C_u$	C_u
		> 30 days	$0,5C_{new,1}+C_u$	C_u
2) Core	2,4	1÷30 days	$0,2C_{new,2}+C_u$	C_u
		> 30 days	$0,5C_{new,2}+C_u$	C_u
3) Bushing	12,0	≤ 1 day	$0,4C_{new,3}$	$0,4C_{new,3}$
		1÷30 days	$C_{new,3}$	-
		> 30 days	$C_{new,3}+C_u$	C_u
4) Tank	7,9	≤ 1 day	$0,1C_{new,4}$	$0,1C_{new,4}$
		1÷30 days	$0,2C_{new,4}$	$0,2C_{new,4}$
		> 30 days	$C_{new,4}+C_u$	C_u
5) On-load tap-changer	40,7	≤ 1 day	$0,1C_{new,5}$	$0,1C_{new,5}$
		1÷30 days	$0,2C_{new,5}$	$0,2C_{new,5}$
		> 30 days	$0,4C_{new,5}$	-
6) Other accessories	10,6	≤ 1 day	$0,1C_{new,6}$	$0,1C_{new,6}$
		1÷30 days	$0,5C_{new,6}$	$0,5C_{new,6}$
		> 30 days	$C_{new,6}$	-

The application of the proposed model is illustrated in the case of a power transformer' station (TS) 110/x kV/kV, where two 31,5 MVA power transformers are installed. Linearized diagram of annual duration of the load for the analyzed TS is shown in Fig. 1 [8]. Maximum load is 80% and minimum 40% of installed capacity, where $P_{instal} = 2 \cdot 31,5 = 63\, \text{MVA}$.

The parameters of distributions were determined based on the data exploitation of the annual intensity of power transformers major failures in the United States (Fig. 1). For adopted mean failure intensity $\lambda_{av} = 0.015\, \text{year}^{-1}$ of the power transformer for the first 30 years of exploitation, based on the curve of Fig. 1 and the data given in **Table 1**, using the least-squares method is obtained parameters of the Weibull distribution for individual components (**Table 4**). In the same table is presented lists of the parameters values in case if at each component individually installed CMS, based on data from **Table 1** and **Table 2** [7, 11].

4   Modelling the Structure of the System Using SDS Method

SDS is used for modelling and simulation of complex dynamic systems with different computer programs [12]. There is a significant application in the analysis of complex dynamic systems, where it is possible to determine what the effects obtained on the system when making certain decisions. By creating SDS model, it is important to understand the causes and consequences of the problem which will be modelling. After the behavior of the system has been examined, dependences between the components in the system will be determined. This method was applied to different kinds of systems: social, environmental, manufacturing, service, biological, agricultural, health, etc. SDS model should have the following characteristics [13]:
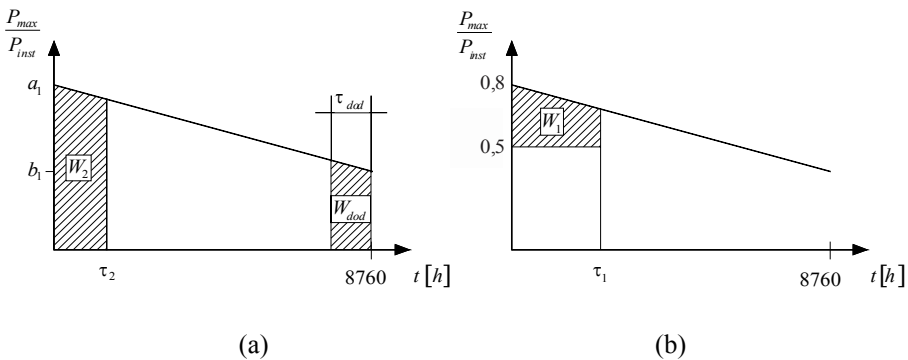

Fig. 1 – *Annual linearized load-duration diagram* $\left(a_1 = 0,8;\, b_1 = 0,4 \right)$.

- describe any problem with the cause - consequence relations,
- the application of mathematical formulas in the simulation system,
- the possibility of applying a large number of variables,
- the analysis of data obtained by simulating a change in the decision.

Each model represents a simplification of the system. To be useful, it does not reflect the system in detail and will depend on the application of the model to solve a problem. The model needs to determine the most important elements of the system. This means simplifying the model, which will not be too complex for the purpose of practical analysis. These models have certain limitations with respect to inaccuracy and errors that can occur due to incorrectly create model.

Table 4
Weibull distribution parameters for components

k	Component	β_k	Without CMS α_k	CMS is available $\alpha_k^{'}$
1	Windings + oil	3,58	57,013	79,805
2	Core	3,58	111,395	155,927
3	Bushing	3,58	74,316	116,500
4	Tank	3,58	102,321	102,321
5	On-load tap-changer	3,58	54,872	80,213
6	Other accessories	3,58	98,808	∞

When applying SDS method for the complex systems behavior analysis, there is commonly used modeling software such as: ARENA, OPEN MODELICA, DYNAMO, DYSMAP, ITHINK/STELLA, POWERSIM, VENSIM, etc.

4.1 VENSIM PLE software for system dynamic modeling

VENSIM PLE software is used for visual modeling that allows creating the models, documentation, system analysis, simulation and optimization of created dynamic systems models. This software tool developed by *"Ventana Systems"* in 1985 for solving management problems by using simulation [14]. On Fig. 2 provides an overview of the software-working environment.

The advantage of this software is that it allows calling external function (programmed in any programming language) that will be used for simulation model. It is possible to import models that were created in other software (such as MATLAB) used for modeling and simulation and adapt for their own needs.

In the models are created different dependencies between variables. Based on defined models it can be made simulations of various events. The model in this software can create as Stock and Flow Diagram (SFD). SFD is used for

displaying the system behavior and the relationship between the variables in the system. Based on these diagrams, the state of the system is determined, as well as the received information on which decisions are being made.
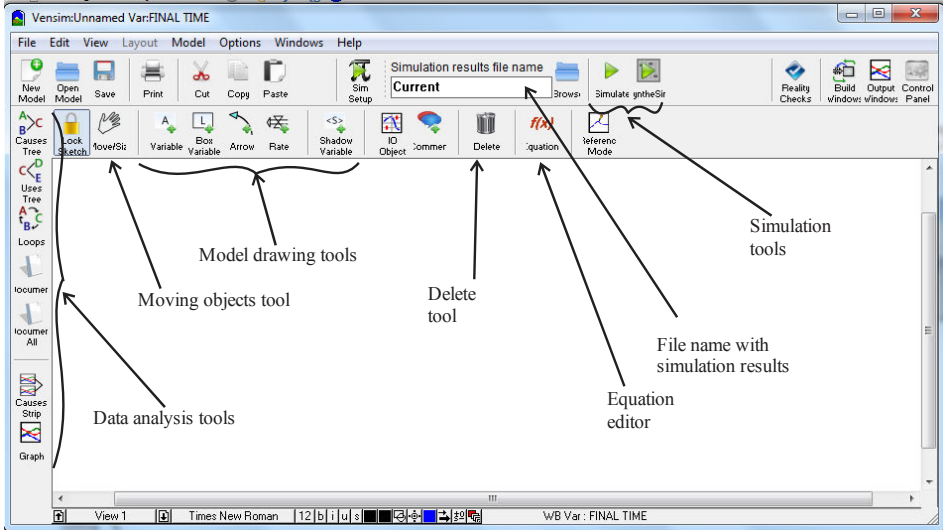

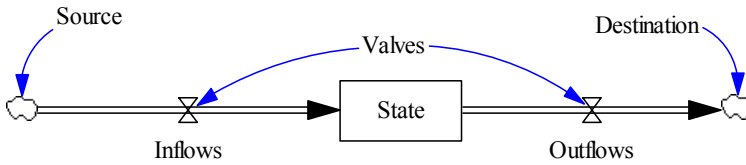**Fig. 2** – *VENSIM PLE working environment.*

Fig. 3 – *The SFD elements.*

The first step of the simulation model is creating this diagram. A certain value has to be assigned to every variable, and formulas important for describing the system behavior should be defined. In the SFD, a dynamic model of the system is represented by the elements shown in Fig. 3. The basic elements of SFD are as follows [15]:

- *Rectangle* – shows different states in time *t*.
- *Inflows* - thicker arrows that enter into rectangle (increases parameters of defined state).
- *Outflows* - coming out of rectangle and represent changes in the state for a time interval $(t, t + dt)$ (reduced values of the state parameters).
- *Valves* - designation that controls input and output variables.

294

- *Clouds* - represent sources and destinations of information flows. Source represents the state from which the model appears, and destinations represent a state of in which information is collected.

4.2 SFD of power transformers maintenance costs

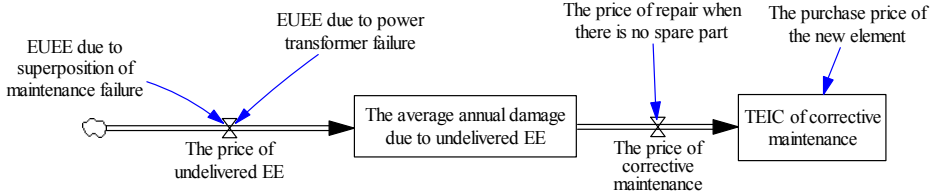When SFD model has been created at the beginning, it must define the initial model parameters.

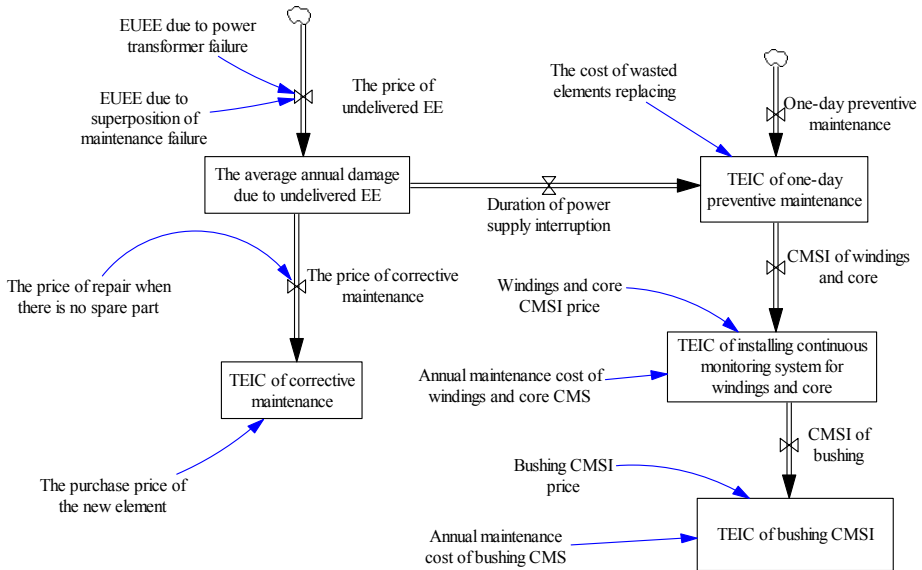**Fig. 4** – *SFD of power transformer corrective maintenance costs.*

Fig. 5 –*SFD of power transformer maintenance costs in case of CMSI.*

For power transformer cost model, the time is displayed in the years and exploitation-planning period of 40 years has been adopted. Based on the proposed model, diagrams of power transformer maintenance costs are designed depending on the type of maintenance that is carried out [16]. SFD of power transformer maintenance costs are showing in Fig. 4 in case of corrective maintenance, and Fig. 5 for the case of installing the CMS.

Abbreviations used in the following figures are:

TEIC – Total Expected Interruption Costs,

EUEE – Expected Undelivered Electrical Energy.

4.3 Simulation of power transformer total expected exploitation costs using Vensim software

To perform a simulation of created model that is represented by the SFD, it is essential to enter correct formula for each using *Equations* icon. The editor is obtained by clicking on any variable as shown in Fig. 6. In the editor section *Variable Information* is enter basic information such as Name, Type, Units, etc. Equations could be entered into the middle part of editor, labeled as *Equations* where it is possible to use the system defined function given in section *Functions*.

If the user enters the wrong name of variable or formula in section *Errors* it will be reported errors review. Sections *Check Syntax* and *Check Model* test the syntax of the given equations and models and perform simulation. If there is any error, the simulation will not start until the error is corrected.

The values that are obtained by simulating the costs could be presented with tools which are found on the right side of the working environment. Fig. 7 shows the graph which simulates the expected total costs of corrective maintenance for planned exploitation period of 40 years. The implementation of this strategy of maintaining obtains the maximum maintenance costs.
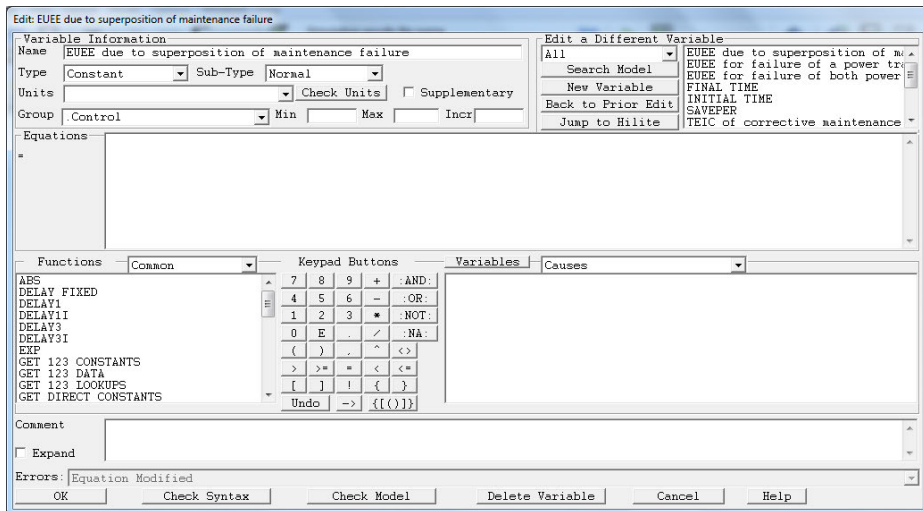

Fig. 6 – *Equation editor for entering formulas and variables.*

Installation CMS of windings and core is justified from the first year of power transformer exploitation. They will be installed at every ten years, as follows: at the beginning of 11th, 21st and 31st exploitation year. Installation CMS of bushings shall be from first exploitation year. It is important to point out that after the implementation of these activities during the planning period of 40 years, it is not justified to implement a one-day maintenance, nor oil regeneration, nor insulation system regeneration. It remains to analyze the justification of spare parts purchase and implementation of power transformer revitalization.
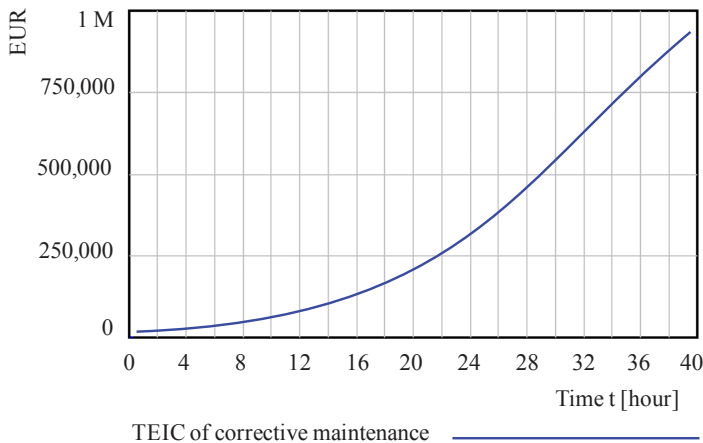
Fig. 7 – *Simulation graph of power transformer total expected mainenance costs in a case of corrective maintenance.*

Gradual analysis has simply calculated that it is justified to obtain spare part of:

- tap charger from the beginning of the 9th year,
- windings since the beginning of the 10th year,
- tank from the beginning of 14th years,
- other equipment from the beginning of 15th years and

implement the revitalization of the transformer at the beginning of 25th year [7]. In this way, there is no need for the acquisition of the spare core.

Simulation of power transformer minimum total expected maintenance costs are obtained in the case of implementing series of activities that are shown in Fig. 7. Here are used VENSIM PLE software tools for drawing these diagrams. On Fig. 8 is presented simulation of costs by installing a system for continuous monitoring of windings, core, bushings and revitalization of power transformer at the beginning of 25 years of exploitation.
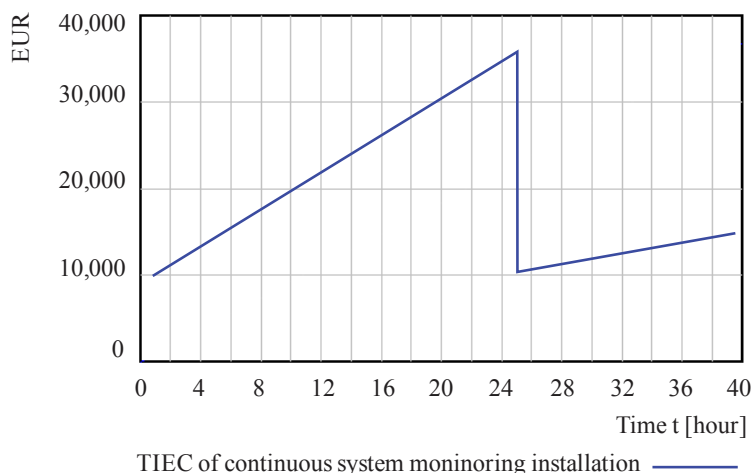
TIEC of continuous system moninoring installation ——————

Fig. 8 – *Simulation graph of power transformer minimal total expected mainenance costs.*

5   Conclusion

The importance of the defined dynamic model is to determine the costs that are incurred upon the supplier of EE and consumers due to the failures occurrence. The implementation of preventive activities such as installing CMS on the transformer components is intended to carry out minimization of costs and increase equipment availability. In addition to these preventive activities can be carried out number of other activities such as spare parts purchasing, the revitalization of transformers, oil changes, etc. All these activities are aimed at reducing costs due to unavailability and increase power transformer exploitation life [17].

Application of the SDS method at cost simulation aims to identify extreme minimum and maximum maintenance costs without the use of a reserve power transformer.

6   Acknowledgement

7   References

[1]   J. Nahman, V. Mijailović: Selected Chapters from the High-Voltage Switchgears, Akademska misao, Belgrade, Serbia, 2002. (In Serbian).

[2]   J. Nahman, V. Mijailović: Reliability of Electrical Distribution System, Akademska misao, Belgrade, Serbia, 2009. (In Serbian).

[3] A. van Schijndel: Power Transformer Reliability Modelling. PhD Thesis, University of Technology, Eindhoven, The Netherlands, 2010.

[4] H. Ge: Maintenance Optimization for Substations with Aging Equipment, PhD Thesis, University of Nabraska –Linkoln, Lincoln, NE, USA, 2010.

[5] G. Nourbakhsh: Reliability Analysis and Economic Equipment Replacement Appraisal for Substation and Sub-Transmisssion Systems with Explicit Inclusion of Non-Repairable Failures, PhD thesis, Queensland University of Technology, Queensland, Australia, 2011.

[6] A. van Schijndel, P.A.A.F. Wouters, E.F. Steennis, J.M. Wetzer: Approach for an Integral Power Transformer Reliability Model, European Transactions On Electrical Power, Vol. 22, No. 4, May 2012, pp. 491 – 503.

[7] O. Ristic, V. Mijailovic: Method for Determining Optimal Power Transformers Exploitation Strategy, Electric Power Systems Research, Vol. 83, No. 1, Feb. 2012, pp. 255 – 261.

[8] V. Mijailovic: Method for Effects Evaluation of Some Forms of Power Transformers Preventive Maintenance, Electric Power Systems Research, Vol. 78, No. 5, May 2008, pp. 765 – 776.

[9] V. Mijailovic: Optimal Spares Availability Strategy for Power Transformer Components, Electric Power Systems Research, Vol. 80, No. 8, Aug. 2010, pp. 987 – 992.

[10] R.A. Jongen, E. Gulski, P.H.F. Morshuis, J.J. Smit, A.L.J. Janssen: Statistical Analysis of Power Transformer Component Life Time Data, 8th International Power Engineering Conference, Singapore, 03-06 Dec. 2007, pp. 1273 – 1277.

[11] A. van Schijndel, J.M. Wetzer, P.A.A.F. Wouters: Remaining Lifetime Modelling for Replacement of Power Transformer Populations, International Conference on Condition Monitoring and Diagnosis, Beijing, China, 21-24 April 2008, pp. 597 – 600.

[12] J. Sterman: Business Dynamics Systems Thinking and Modeling for a Complex World, Irvin - McGraw Hill Higher Education, ISBN 0 - 07 - 231135 - 5, 2000, 982 p.

[13] E. Kremers: Modelling and Simulation of Electrical Energy Systems through a Complex Systems Approach using Agent-Based Models, PhD Thesis, KIT Scientific Publishing, Karlsruhe, Germany, 2013.

[14] http://vensim.com/

[15] P. Basirat, H. Fazlollahtabar, I. Mahdavi: System Dynamics Meta-Modelling for Reliability Considerations in Maintenance, International Journal of Process Management and Benchmarking, Vol. 3, No. 2, 2013, pp.136 – 153.

[16] R. Chumai: System Dynamic Modeling of Plant Maintenance Strategy in Thailand, 27th International Conference of the System Dynamics Society, Albuquerque, NM, USA, 26-30 July 2009.

[17] O. Ristić: Dynamic Modeling and Simulation of Preventive Exploitation Activities in Electric Equipment Reliability Analysis, PhD Thesis, University of Kragujevac, Serbia, June 2016. (In Serbian).