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MULTISTAGE FUZZY OPTIMIZATION OF THE PEAK POWER

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Abstract. *A new method for multistage fuzzy optimization of the peak power is presented in this paper. Fuzzy concluding in several stages at cascade-connected systems is considered where the fuzzy parameters in one stage are determined by fuzzy concluding in the previous stage. This method is employed in the optimization of the electric energy consumption using peak power control.*

Key words: *fuzzy parameters, cascade-connected system, peak power optimization*

1. INTRODUCTION

In the long history of the control systems design, it is noticed that many processes have imprecise parameters [1]. One way of dealing with these parameters is the use of interval analysis [2]. Imprecision of the parameters can be also dealt with fuzzy logic and fuzzy parameters use [3], [4]. On the other hand, the history of designing systems for optimization of the peak power in the industry showed that it is possible to determine single parameters of the systems for peak power optimization by fuzzy logic in the previous stage based on economic indicators. In the case of the peak power optimization, these indicators are the level of the raw materials, the amount of the final products and the market demands for the final products in the previous month. We can say that in this case we have determining of parameters necessary for the scaling of the universal set in the algorithm for fuzzy optimization of the peak power. As an example of our method application, a system for optimization of the peak power in the tire industry is considered. It has been demonstrated that the application of fuzzy logic has advantages over the classical methods. For the optimization of the peak power, linear prognosis of the peak power during fifteen-minute intervals has been used.

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2. PEAK POWER OPTIMIZATION

It is known that peak power can be defined as maximum fifteen-minute energy consumption in a plant during one month. We can notice that there are 2880 (4x24x30) of these intervals in one account period. For peak power charging, only maximum fifteen-minute consumption is considered. Therefore, the goal of peak power optimization is to make this interval peak consumption as little as possible with maximum overall plant production (maximum plant profit). We should also notice that the consumption of the active energy E is proportional to the given plant production. There are several existing algorithms [2]-[8], dealing with this problem with the final goal to derive unified criteria for conflicting conditions for overall consumption and peak power.

One of the possible criteria is the following:

$$J = k_1 \int_0^{T_M} P(t)dt - k_2 \frac{\max\limits_{t=iT\in T_M} P_{M_i}}{\frac{1}{T_M}\int_0^{T_M} P(t)dt}, \tag{1}$$

and

$$P_{M_i} = \frac{\int_0^{T} P_i(t)dt}{T}, \tag{2}$$

where i represents the number of fifteen-minute interval, $P(t)$ - current plant power, T_M – optimization period, T – fifteen minute interval. Criteria J is calculated in euros [€] and k_1 [€/kWh] and k_2 [€] are weight coefficients.

With regard to relations (1) and (2), we need to estimate consumed fifteen minute energy $E(T)$, where T=15 min. Usually, this value is estimated based on consumption during previous month and production estimation in the current month. Essentially, optimization algorithm is based on such a control during fifteen minutes that, with some limitations, drive the system from initial state to the preset point ($E(T)$). In other words, we are "targeting" the point $E(T)$ at the end of a fifteen minute interval as it is shown in Fig. 1.

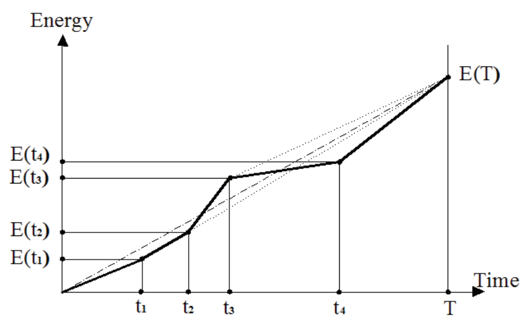

Fig. 1 Linear prognosis in the systems for optimal control of electric energy consumption

Optimization can be performed by linear or nonlinear prognosis. In the case of linear prognosis for estimation of consumed fifteen-minute energy, prognosis algorithm is based on the following equation:

$$E\left(t\right)=\frac{E(t)-E(t_k)}{T-t_k}t+E(t_k)\ , \tag{3}$$

where: $E(t_k)$ – plant energy in the moment t_k, $E(t)$ - current plant energy, $E(T)$ – given overall fifteen-minute plant energy. Current energy $E(T)$ given in this manner, has to be smaller than $E(T)$ in every calculation moment in order to secure the plant operating in the limitations of the given parameters.

The second approach is nonlinear prognosis of the electric energy consumption that enables continuous control of the machines power, where this possibility exists. For the simplicity, consider nonlinear parabolic curve ($E = at^2 + bt + c$). Graphical interpretation of this kind of nonlinear prognosis is given in Fig. 2, where y_r represents preset value that cannot be exceeded over interval (0, t_r).

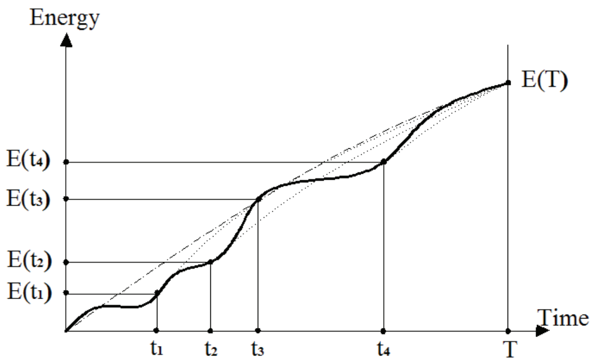

Fig. 2 Nonlinear parabolic prognosis

Interval (0, t_1) is interpolated with parabola $E = at^2 + bt + c$. After the change (increase or decrease of overall plant machines power) in moment t_1 interpolation takes new parabola determined by equation $E_1 = a_1t_1^2 + b_1t_1 + c_1$, until the next change in moment t_2 when interpolation relation becomes $E_2 = a_2t_2^2 + b_2t_2 + c_2$ and so on. Coefficients determining these parabolic curves can be calculated in several different manners. Parabola is determined by three equations in points $E(t_k)$, $E(t)$ and $E(T)$. Relation for the nonlinear prognosis is:

$$E(t)=\frac{E(t_k)T-E(T)t_k}{T(T-t_k)^2}t^2+\frac{E(T)T^2-2E(t_k)T^2+E(T){t_k}^2}{T(T-t_k)^2}t+\frac{T(E(t_k)T-E(T)t_k)}{(T-t_k)^2}\ . \tag{4}$$

The following condition must also be fulfilled because current plant power has to be smaller than the overall installed power:

$$\frac{dE(t)}{dt} \le \sum_{j=1}^{n} P_j \ . \tag{5}$$

Parameters of the control system need to be adjusted during the process of peak power optimization. The most important parameter to be set is a given fifteen-minute energy consumption. It is set based on the information of fifteen-minute peak power during the previous month (E_i) and the change of fifteen-minute peak power during the previous month ($\Delta E_i = E_i - E_{i-1}$). Realization of these two conditions is usually done proportionally, by differential concluding. On the other hand we should notice that the decision for adjustment of the given fifteen-minute peak power based on these conditions can be performed by fuzzy concluding if we define adequate fuzzy sets for the given fifteen-minute peak power in the previous interval and for the change of the same power.

Algorithm based on these data can be improved by including some other economical indicators:

a) the amount of raw materials in the input storage,
b) the amount of final products in the output storage and
c) market demand for the final products during the previous month.

3. Multistage Parameters Determining in a Fuzzy Environment

There are several papers about multistage control in fuzzy environment [9], [10]. This concept includes determining parameters in the next stage (cascade) based on the parameters in the previous stage. In our case, concluding is performed in fuzzy environment related to parameters, not to state coordinates. In general, we can consider M cascade-connected subsystems with single parameters of fuzzy type. This type of fuzzy concluding with overall M parameters is shown in Fig. 3.

This method of concluding is used in described system for peak power optimization. Two-stage parameters adjustment is performed in fuzzy environment. In this case, fuzzy environment is represented with economical indicators mentioned above (E_i, ΔE_i, a, b, c). Based on indicators a, b and c in the first cascade of fuzzy determining; scaling coefficient K_{Td} is first calculated. The next step is a scaling of universal set in the second cascade based on previously determined K_{Td}. With E_i, ΔE_i and given scaled universal set, we obtain desired fifteen-minute peak power that can be written into maxi graph for the current month.

As we can see from Fig. 3, fuzzy parameters for ($m+1$) cascades are determined with the concluding in m-th cascade based on fuzzy rules in the same cascade. Most usual parameters that can be calculated via fuzzy logic are scaling factor for the universal fuzzy set, membership functions parameters (begin, middle and end points), shape of the membership functions…

For every parameter in m-th cascade (a_n^m) we define a membership function $\mu_{A_n m}(a_n^m)$ where $n \in 1,2,...,N$ represents the number of parameter or data. Then we apply algorithm for fuzzy concluding on every parameter or data in the following cascade a^{m+1}, $m \in 1,2,...,M$ similar to the classical fuzzy concluding (e.g. Mamdani algorithm) where fuzzy relations have the following shape:

$$\begin{array}{l} \mu_{A_1 1}(a_1^1) \wedge \mu_{A_2 1}(a_2^1) \wedge \ldots \mu_{A_n 1}(a_n^1) \wedge \ldots \mu_{A_N 1}(a_N^1) \Rightarrow \mu_{B1}(a^2) \\ \vdots \\ \mu_{A_2 1}(a_1^m) \wedge \mu_{A_2 m}(a_2^m) \wedge \ldots \mu_{A_n m}(a_n^m) \wedge \ldots \mu_{A_N m}(a_N^m) \Rightarrow \mu_{Bm}(a^{m+1}) \\ \vdots \\ \mu_{A_2 M}(a_1^M) \wedge \mu_{A_2 M}(a_2^M) \wedge \ldots \mu_{A_n M}(a_n^M) \wedge \ldots \mu_{A_N M}(a_N^M) \Rightarrow \textit{final decision} \end{array} , \quad (6)$$

or in the shorter form:

$$\bigwedge_{n=1}^{N} \mu_{A_N m}(a_n^m) \Rightarrow \mu_{Bm}(a^{m+1}),\ m = 1, 2, ..., M\ . \quad (7)$$

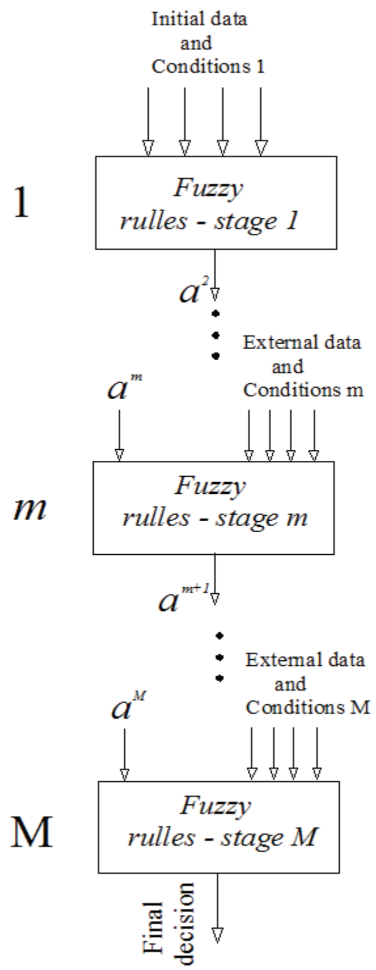

Fig. 3 Multistage parameters determining in a fuzzy environment

In the general case, if there is a need for determining multiple parameters in the fuzzy environment then we can use the structure given in Fig. 4 where every cascade has more than one input parameters from the previous cascade and a few additional data, specific and needed for that concrete cascade.

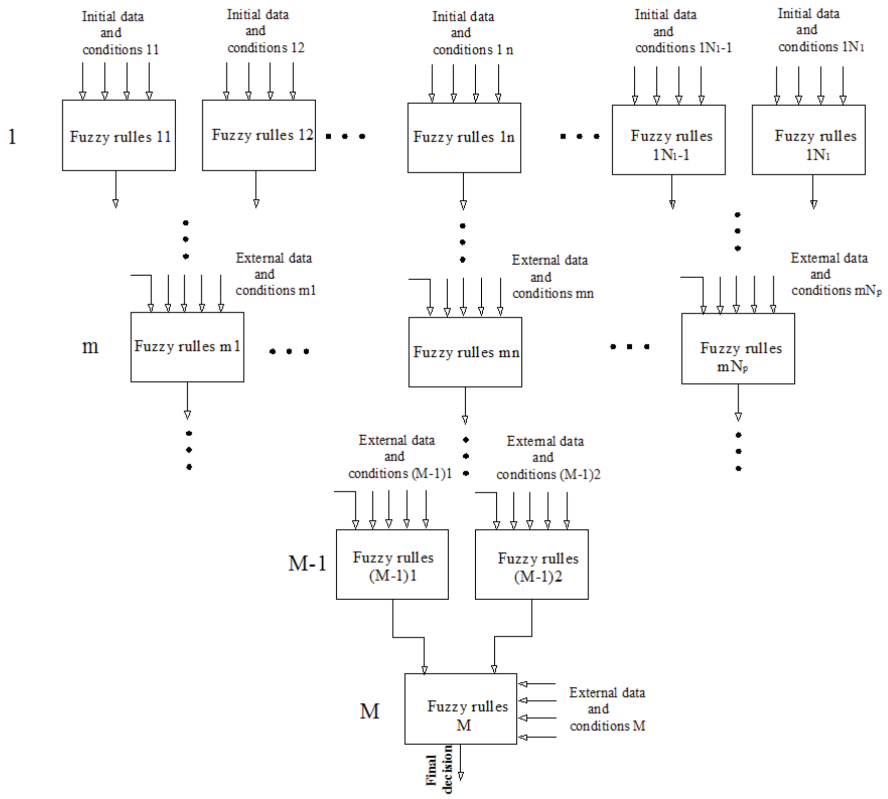

Fig. 4 General block diagram for multi parameters determining in the multi stage fuzzy environment

4. MULTISTAGE FUZZY LOGIC APPLIED IN PEAK POWER OPTIMIZATION

Systems for optimal electric energy consumption have enabled the operator to adjust process parameters in order to make as big as possible cost savings. However, this possibility can induce many problems in practice. The operator, in most cases, adjusts limit value of maximum engaged fifteen-minute energy according to the production plan, the amount of row materials in the input storage, the amount of final products in the output storage, market trends, workers holidays... This can be a very complicated process, prone to errors, especially today with the current development of informatics technologies. It is very difficult for the operator to supervise equally all the parameters and to manage optimal operating regime with the minimum expenses.

For example, if the operator does not correct preset limit for the maximum engaged fifteen-minute energy, before the plant begins to operate with the decreased capacity, an absurd situation can arise. The money dedicated for electric energy needed for production can become smaller than the money for the reached maximum engaged fifteen-minute energy, read from the maxi graph. This is the penalty for unequaled energy consumption. One of the solutions of this problem was to use some look up tables for determining the maximum engaged power, but this solution also had its own drawbacks. Practical problems proved that the only possible good solution had to decrease the role of the operator in decision-making. Control part of the algorithm has to be completely separated from the operator.

Basic information about peak power is the following: raw amount in the input storage (R), final products amount in the output storage (P) and market demands for the final products (MD). These pieces of information will be linguistic variables in our fuzzy deciding. According to the previous descriptions, denote: $R = a_1^1$ (one in the subscript is for the number of the parameter and one in the superscript is for the number of the cascade), $P = a_2^1$ and $MD = a_3^1$. Label the values of these linguistic variables with small (S), medium (M) and large (L) together with the corresponding membership functions shown in Fig. 5.

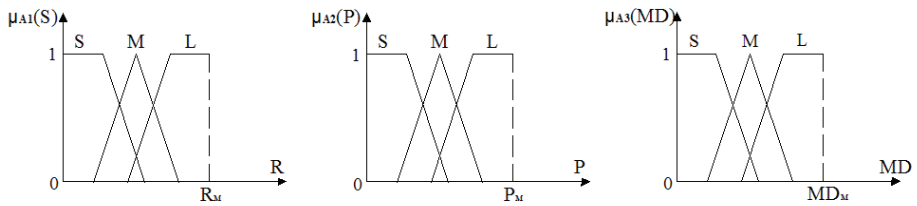

Fig. 5 Membership functions for input fuzzy sets R, P and MD

As we can see from Fig. 5, universal sets are defined for the variable R over interval (0, R_M), for variable P over (0, P_M) and for MD over (0, MD_M). As for output variable fuzzy set K_T shown in Fig. 6, (analog to the output set of parameter at the output of the first cascade $K_T = a_1^2$), we have interval (0, K_{TM}).

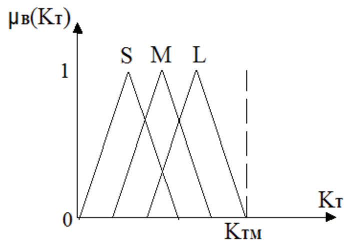

Fig. 6 Membership functions for the output set of scaling coefficient (K_T)

Fuzzy rules are given with the following relations:

$$\begin{array}{l}\text{IF } R \text{ is small AND } P \text{ is small AND } MD \text{ is small THEN } K_T \text{ is small} \\ \vdots \\ \text{IF } R \text{ is medium AND } P \text{ is medium AND } MD \text{ is medium THEN } K_T \text{ is medium} . \\ \vdots \\ \text{IF } R \text{ is large AND } P \text{ is large AND } MD \text{ is large THEN } K_T \text{ is large}\end{array} \quad (8)$$

There are three linguistic variables (R, P, MD) with three possible values each (S, M, L), so there are 27 rules. Fuzzy rules given with (8) can be also written in the logical form:

$$\begin{array}{l}\mu_{A_2S}(R)\wedge\mu_{A_2S}(P)\wedge\mu_{A_2S}(MD)\Rightarrow\mu_{BS}(K_T) \\ \vdots \\ \mu_{A_2M}(R)\wedge\mu_{A_2M}(P)\wedge\mu_{A_2M}(MD)\Rightarrow\mu_{BM}(K_T) . \\ \vdots \\ \mu_{A_2L}(R)\wedge\mu_{A_2L}(P)\wedge\mu_{A_2L}(MD)\Rightarrow\mu_{BL}(K_T)\end{array} \quad (9)$$

Finally, after applied centroid defuzzyfication, we obtain determined output K_{Td}:

$$K_{Td} = \frac{\int_0^{K_{TM}} \mu_B(K_T)K_T dK_T}{\int_0^{K_{TM}} \mu_B(K_T) dK_T} . \quad (10)$$

Coefficient K_{Td} is multiplied with maximum value E_T and we obtain universal set K_{Td} E_T. From this set, we can further determine maximum engaged fifteen-minute energy, which can be used in the second stage of fuzzy concluding.

In the second stage, we define input membership functions (Fig. 7) for consumed electric energy ($E_i = a_1^2$) and the change of this energy ($\Delta E_i = E_i - E_{i-1} = a_2^2$) in the previous month.

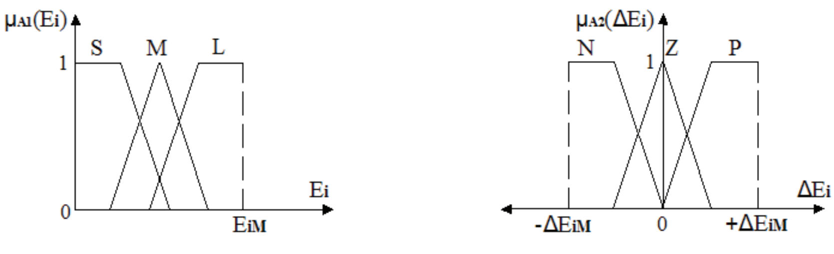

Fig. 7 Membership functions for consumed energy (E_i) and the change of consumed energy (ΔE_i)

Universal set for E_i is defined over interval (0, E_{iM}) and for ΔE_i over ($-\Delta E_{iM}$,$+\Delta E_{iM}$). Labels in the figure have the following meaning: *N*-negative, *Z*-about zero, *P*-positive, *S*-small, *M*-medium, *L*-large. The next step is to define output fuzzy set, i.e., membership functions for the maximum engaged fifteen-minute energy E_T. Figure 8 shows corresponding membership functions for E_T.

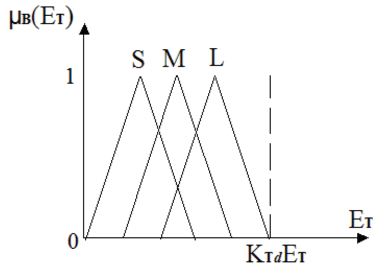

Fig. 8 Membership functions for the output set of maximum engaged fifteen-minute energy E_T

Rules for fuzzy deciding can be written in proportional-differential manner (PD like fuzzy controller):

$$\begin{aligned}
&\text{IF } E_i \text{ is small AND } \Delta E_i \text{ is negative THEN } E_T \text{ is small}\\
&\vdots\\
&\text{IF } E_i \text{ is medium AND } \Delta E_i \text{ is about zero THEN } E_T \text{ is medium}\,.\\
&\vdots\\
&\text{IF } E_i \text{ is large AND } \Delta E_i \text{ is positive THEN } E_T \text{ is large}
\end{aligned} \tag{11}$$

Two linguistic variables E_i and ΔE_i, with three values each, result in nine rules that can also be written in logical form:

$$\begin{aligned}
&\mu_{A_2 S}(E_i) \wedge \mu_{A_2 N}(\Delta E_i) \Rightarrow \mu_{BS}(E_T)\\
&\vdots\\
&\mu_{A_2 M}(E_i) \wedge \mu_{A_2 Z}(\Delta E_i) \Rightarrow \mu_{BM}(E_T)\,.\\
&\vdots\\
&\mu_{A_2 L}(E_i) \wedge \mu_{A_2 P}(\Delta E_i) \Rightarrow \mu_{BL}(E_T)
\end{aligned} \tag{12}$$

Finally, limitation value of engaged fifteen-minute energy E_{Tg} can be determined by using centroid defuzzyfication:

$$E_{Tg} = \frac{\int_0^{K_{Td}E_T} \mu_B(E_T) E_T \, dE_T}{\int_0^{K_{Td}E_T} \mu_B(E_T) \, dE_T}\,. \tag{13}$$

The obtained value E_{Tg} represents an input for the algorithm for optimal control of electric energy consumption.

5. CASE STUDY

For the purposes of valorization of the proposed algorithm for peak power optimization, we considered rubber factory "Vulkan-Nis", given in Fig. 9. The plant produces transport strips, hoses and rubbery boots. The overall installed power of all machines in the factory is $P = 10MW$. The plant, itself, consists of several interconnected technological production units. Our optimization algorithm realizes single switching on and off by changing the powers of consumers and time distributed switching.

For the specific input values R^*, P^* and MD^* using the fuzzy concluding of the Mamdani type, we obtain the corresponding output fuzzy set, whose defuzzyfication determines the value of scaling coefficient for the universal set K_{Td}. The value of scaling coefficient K_T is defined by $K_T \leq 1$.

Using the software package MATLAB, in the case of input values determined by R^*, P^* and MD^*, on the basis of defined rules (8) and (9) we will be determined the output value for the scaling coefficient K_{Td}. All input and output sets will be normalized, that is, their values will be located in the range from 0 to 1. If we assume the following values for the input parameters: the raw amount in the input storage R^*=0.35, the final products amount in the output storage P^*=0.55 and market demands for the final products MD^*=0.3 we will obtain for the scaling the value of the universal set K_{Td} =0.37.

The obtained value K_{Td} =0.37 is used in the second stage, so that it scales a universal set for maximum engaged fifteen-minute

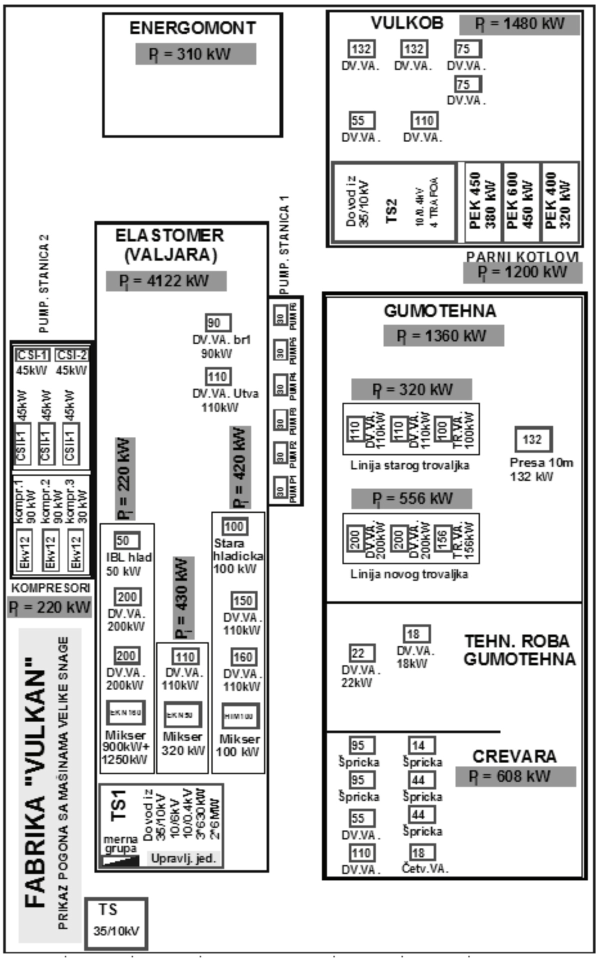

Fig. 9 Block scheme of the rubber system in tire industy Vulkan, Nis

energy, which is then used to determine limitation of engaged fifteen-minute energy using PDF regulator. For the normalized values of plant power $E_i^*=0.75$, and energy change $\Delta E_i^*=0.3$, as determined input values, with a universal set, scaled by coefficient $K_{Td}=0.37$ we obtained using the defined rules (12) and defuzzyfication (13) determined output value of engaged fifteen-minute energy $E_{Tg}=0.242$. This output value for limitation engaged fifteen-minute energy $E_{Tg}=0.242$, obtained using fuzzy logic, represents the input for the algorithm for the peak power optimization.

6. CONCLUSION

In this paper we proposed a new method for optimal determining the desired peak power during the current month, based on multistage fuzzy logic. The necessary mathematical background for this method is also given. Its advantage is in determining the desired (target) values of peak power based on parameters a, b, c, E_i and ΔE_i (in the fuzzy environment). In this manner, information about the work of the system in real conditions, and target peak power are determined in the best possible way. Using this algorithm the system for peak power optimization is designed. The exploitation of this system gives better results compared to the traditional methods. The same algorithm can also be applied in case of other processes and systems in which it is necessary to make conclusions in several stages in the fuzzy environment.

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VIŠEETAPNA FAZI OPTIMIZACIJA VRŠNE SNAGE

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U radu je prikazan jedan metod za višeetapnu fazi optimizaciju vršne snage. Izložen je način za višeetapno fazi zaključivanje kod kaskadno povezanih sistema. Fazi parametri u određenoj kaskadi određuju se fazi zaključivanjem u prethodnoj kaskadi. Dat je primer gde je ova metoda primenjena u cilju optimizacije potrošnje električne energije regulacijom vršne snage.

Ključne reči: *fazi parametri, kaskadni sistem, optimizacija, vršna snaga.*