

# POLYOPTIMISATION OF SYNCHRONOUS GENERATOR FUZZY VOLTAGE REGULATOR

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The paper presents the method for multicriteria design of a synchronous generator voltage regulator. The results of the voltage regulator polyoptimization are compromise sets for a classic controller of type PI and fuzzy logic controller of type Takagi-Sugeno-Kang. A genetic algorithm is used to solve the polyoptimization problem.

**Key words:** polyoptimisation, synchronous generator, fuzzy controller

## 1 INTRODUCTION

The dynamic development in the field of electrical engineering, in particular growing requirements in the matter of reliability and accessibility of supply, has resulted in widespread use of autonomous supply sources. The most popular of them is a synchronous generator driven by an internal combustion engine (ICE) due to its simple construction and resistance to external disturbances. In these units there are applied different stabilizing systems in order to keep the voltage at a constant level. The electronic systems of automatic regulation are used in those of high output voltage quality.

The increase in stabilization accuracy of the synchronous generator voltage, especially in transient states, can be achieved by optimization of regulation system subsets. However, searching for the optimal solution basing on general criteria (ieintegral criteria [3]) not closely connected with the regulation object does not always result in a solution meeting all the given requirements [7]. In the case of high requirements and a number of contradictory criteria, the regulation object can be polyoptimized [7, 8, 9].

In a classical approach, the optimization consists in such changes of the regulation system parameters as to minimize one quality factor. Thus, the optimal solution is a point in the space of permissible values of the quality factor analyzed. When performing the polyoptimization of a regulation system, one searches for a set of optimal solutions minimizing the set of quality factors [9]. The polyoptimization result is the set of optimal solutions (set of groups of the regulation system parameters) and the minimum values of the quality factors are the so-called compromise set in the space of their permissive values. It can be proved that every point of compromise set is the extremum of one equivalent quality factor in a form of a weighted sum of the polyoptimization quality factors, therefore polyoptimization can be treated as a generalization of optimization [1, 9].

The controller “regulation properties” are described by the quality factor value in the classic approach, while in the polyoptimization process they are described by the compromise set.

## 2 ESSENTIALS OF POLYOPTIMIZATION

As mentioned before, the result of the performed polyoptimization is the compromise set  $\Lambda$ , and it is a hyper-surface in  $n$ -dimensional objective space  $\mathbf{Q}$  [9], where  $n$  is the number of quality factors optimized. The objective space is determined by the permissible values of the quality factors optimized (partial objective functions)  $Q_i$ . Since the quality factors  $Q_i$  are functions of the optimized parameters, the objective space  $\mathbf{Q}$  is an image of  $m$ -dimensional control space  $\mathbf{X}$  [9], where  $m$  is the number of the regulation system parameters optimized.

In the minimization problem the compromise set  $\Lambda$  is described by the following equation [9]:

$$\{\tilde{Q}_1, \tilde{Q}_2, \dots, \tilde{Q}_n\} \in \Lambda \iff \neg \exists \{Q_1, Q_2, \dots, Q_n\} \in \mathbf{Q}: \left\{ \begin{array}{l} Q_i \leq \tilde{Q}_i \text{ for each } i \in \langle 1, 2, \dots, n \rangle \\ Q_i < \tilde{Q}_i \text{ for at least one } i \in \langle 1, 2, \dots, n \rangle \end{array} \right\}, \quad (1)$$

where:  $\{\tilde{Q}_1, \tilde{Q}_2, \dots, \tilde{Q}_n\}$  — member of the compromise set,  $\{Q_1, Q_2, \dots, Q_n\}$  — member of the objective space.

Since the analytical determination of the compromise set for complex regulation systems can be difficult, there is determined the so-called discrete compromise set by performing the repeated optimization of all the quality factors  $\Lambda_D$  simultaneously [9]. The discrete compromise set  $\Lambda_D$  consists of the points  $\{\tilde{Q}'_1, \tilde{Q}'_2, \dots, \tilde{Q}'_n\} \in \mathbf{Q}$  and, in the general case, is the approximation of the compromise set  $\Lambda$ . Neglecting the inaccuracy of iterative determination of extrema, a genetic algorithm was used for solving the polyoptimization problem in the presented investigations. It was the algorithm with selection of simultaneous tournaments enabling searching for extrema of many functions [11].

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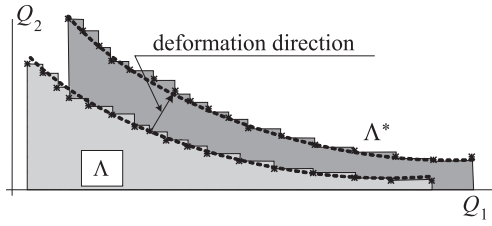


Fig. 1. Compromise set deformation.

The important problem when analyzing regulation systems is to determine the influence of unfavourable factors on the regulation quality. This influence is determined basing on changes of the optimized quality factor values due to the analyzed unfavourable factor [1, 3]. A similar approach is assumed in the polyoptimization where more than one quality factor changes — it is the whole compromise set that changes. Hence, it is possible to introduce a concept of the compromise set deformation [7]. For a discrete compromise set the deformation is a change of position of this set points in the objective space analyzed. Fig. 1 shows the graphical interpretation of the compromise set deformation for 2-dimensional objective space.

### 3 MATHEMATICAL MODEL OF AN INTERNAL COMBUSTION ENGINE AND A SYNCHRONOUS GENERATOR

In the presented investigations a generating unit operating alone is assumed to be a regulation object. It consists of a 4 kVA salient pole synchronous generator of Gce32b type and a 6 kW Diesel engine of type Hatz 1B40 rotating with the constant speed.

When neglecting the changes of the moment of inertia of the generating unit rotating mass  $J$ , due to, among others, the construction of the driving motor assembly of a crank-shaft, the rotary motion of the unit is described by the equation [4]:

$$J \frac{d\omega}{dt} = T_m(t) - T_e(t), \quad (2)$$

where:  $\omega$  — angular speed,  $T_m$  — ICE torque,  $T_e$  — generator torque.

In order to model the ICE torque  $T_m$ , the partial characteristics of the investigated ICE torque were approximated by a polynomial of the third order. Moreover, the analysis of the influence of the delivered fuel quantity  $\xi$  on the coefficient values of the polynomial approximating the torque was performed. It was stated that this influence can also be approximated by a polynomial of the third order. For such assumptions, the driving torque of the ICE is given by:

$$T_m(\omega, \xi) = \left( \begin{bmatrix} b_{00} & b_{10} & b_{20} & b_{30} \\ b_{01} & b_{11} & b_{21} & b_{31} \\ b_{02} & b_{12} & b_{22} & b_{32} \\ b_{03} & b_{13} & b_{23} & b_{33} \end{bmatrix} \begin{bmatrix} 1 \\ \xi \\ \xi^2 \\ \xi^3 \end{bmatrix} \right)^T \begin{bmatrix} 1 \\ \omega \\ \omega^2 \\ \omega^3 \end{bmatrix}, \quad (3)$$

where:  $b_{00}$  to  $b_{33}$  are coefficients of the polynomials approximating the driving motor torque.

Due to the existing inertia of the ICE supply system, the actual value of the fuel dose  $\xi$  is described by the equation of the injection pump together with the proportional controller of the ICE rotary speed:

$$\tau_{zp} \frac{d\xi}{dt} + \xi = k_{rn}(n_z - n), \quad (4)$$

where:  $\tau_{zp}$  — time constant of the injection pump inertia,  $k_{rn}$  — speed controller amplification,  $n_z$  — given speed value,  $\xi \in \langle \xi_{\min}, \xi_{\max} \rangle$  where  $\xi_{\min}$ ,  $\xi_{\max}$  is the limit amount of the delivered fuel.

There were taken into account one equivalent damping circuit of the field magnet in the longitudinal ( $d$ ) axis and one in the transverse ( $q$ ) axis in the synchronous generator mathematical model. Assuming the symmetry of the machine and the constant permeability of the core, after making Park transformation of differential equations, the synchronous generator mathematical model is represented by the equivalent diagrams for particular machine axes (Fig. 2), the symbol  $\bullet$  denotes that the field magnet circuits are in armature terms.

The synchronous generator equivalent diagrams are described by the following matrix equation:

$$\mathbf{U} = \mathbf{R}\mathbf{I} + \mathbf{L} \frac{d\mathbf{I}}{dt} + \mathbf{\Omega}\mathbf{L}\mathbf{I}, \quad (5)$$

where:  $\mathbf{U}$  — vector of axial voltages,  $\mathbf{I}$  — vector of axial currents,  $\mathbf{\Omega}$  — matrix of pulsations,  $\mathbf{R}$  — matrix of resistances,  $\mathbf{L}$  — matrix of inductances.

The likelihood of the simulation investigation results depends highly on the accuracy of determining the parameters of the mathematical model assumed. That is why a two-stage method for determining the mathematical model parameters was assumed. Resistances and inductances of the equivalent diagrams (Fig. 2) are the parameters of the synchronous generator mathematical model. At the first stage the relationships valid in steady states of the generator (short-circuit and no-load) were used. They made it possible to determine the parameters  $R$ ,  $R_f$ ,  $L_d$  and  $L_q$ . The other model parameters, that is  $R_{td}$ ,  $R_{kq}$ ,  $L_\sigma$ ,  $L_{f\sigma}$ ,  $L_{td\sigma}$ ,  $L_{kq\sigma}$ , were determined at the second stage which was based on analyzing the phenomena occurring in the generator transient states. A hybrid algorithm was used for determining the values of the searched parameters at the second stage. The approximation error of the generator waveforms in transient states, that is in short-circuit and switching on the field voltage of the non-excited generator, was minimized. The hybrid algorithm applied was a combination of the genetic and Nelder-Mead algorithm [7].

The block diagram of the analyzed generating unit model corresponding to the presented above mathematical models of the component elements is shown in Fig. 3.

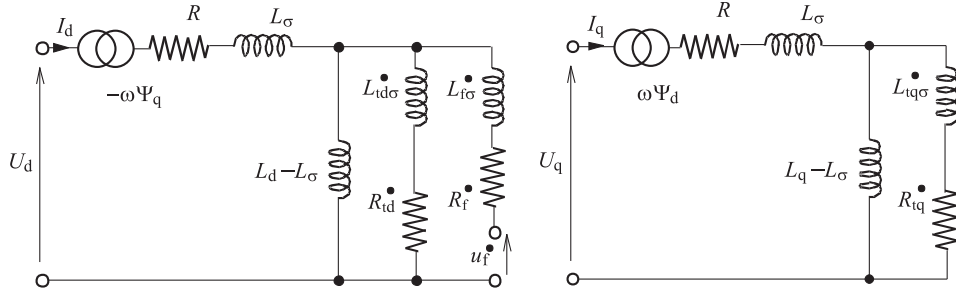


Fig. 2. Equivalent diagrams of a synchronous generator.

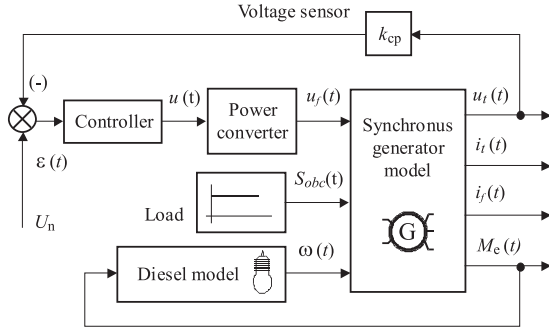


Fig. 3. Block diagram of the generating unit model.

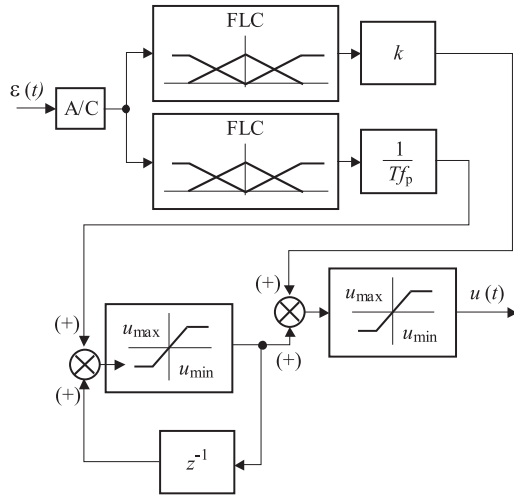


Fig. 4. Block diagram of a fuzzy controller.

#### 4 POLYOPTIMISATION OF THE VOLTAGE REGULATOR SETTINGS

A fuzzy logic PI controller with Takagi-Sugeno-Kang implication system (TSK-PI) [2, 12] of parallel structure corresponding to a classic PI controller [7, 5] was used for regulation of the synchronous generator voltage in the presented investigations. In order to determine the controller output signal value, the method of weighted mean was applied [3]. The investigations were carried out for the controller structure shown in Fig. 4. The assumed fuzzy logic controller corresponds as to its functions to the commonly used controller in which the implication is

performed on the basis of the error value and its increment [12]. The structure assumed is poorer and simpler in practical realization. However, it enables tuning the proportional and integral part independently of each other (as for the classic PI controller).

In order to simplify the optimization procedure in the investigated controller, the same fuzzy systems were assumed in the proportional and integral part (Fig. 4). The fuzzy system with three functions of antecedent and consequent membership (Fig. 5) and three rules of knowledge basis were considered:

- IF  $\varepsilon$  is U THEN  $u$  is U,
- IF  $\varepsilon$  is Z THEN  $u$  is Z,
- IF  $\varepsilon$  is D THEN  $u$  is D.

For the fuzzy logic controller mentioned above the amplification  $k$  and time constant  $T$  were optimized for different, parametrically changed values of the sampling frequency.

According to the number of requirements imposed, one can select any number of quality factors for polyoptimization. In order to present the results graphically, two quality factors optimized simultaneously and resulting from the requirements imposed on a voltage regulation system by the standard [10] were assumed for the investigations carried out.

- Integral quality coefficient  $Q_{ITSE}$ :

$$Q_1 = Q_{ITSE} = \int_0^{t_r} t(\epsilon(t))^2 dt, \quad (6)$$

where:  $t_r$  – setting time,  $\epsilon$  – control error.

The setting time was defined as a time between the instant of the disturbance occurrence (in the analyzed case — applying the rated load) and the instant of reaching a new steady state. It was assumed that the new steady state was reached at the moment for which the control error was reduced permanently below 0.5% of the given value [10].

- Factor of the relative peak-to-peak oscillation of the controller output signal in steady state for the generator rated load  $Q_L$ :

$$Q_2 = Q_L = \frac{\max(u(t)) - \min(u(t))}{u_0} 100\%, \quad (7)$$

where:  $u(t)$  – instantaneous value of the controller output signal,  $u_0$  – constant component of the controller output signal in steady state for the generator rated load.

The searched compromise sets for the fuzzy logic controller (Fig. 4) at different sampling frequency were determined by performing the repeated optimization with the use of a genetic algorithm. The compromise sets obtained were compared with those determined for the classic PI controller (Fig. 6) for which the amplification  $k_{PI}$  and time constant  $T_{PI}$  were optimized.

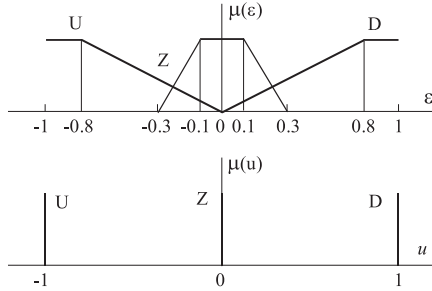


Fig. 5. Membership function of a fuzzy controller.

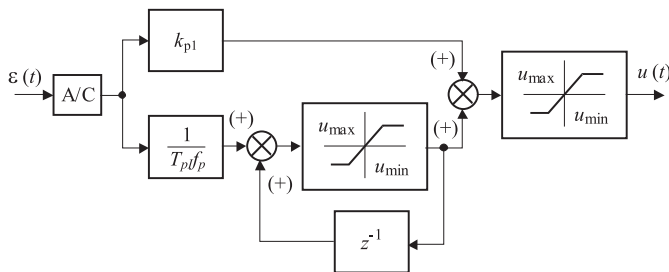


Fig. 6. Block diagram of a classic controller type PI.

The results of polyoptimization of the fuzzy and classic controller settings for different sampling frequency are shown in Fig. 7.

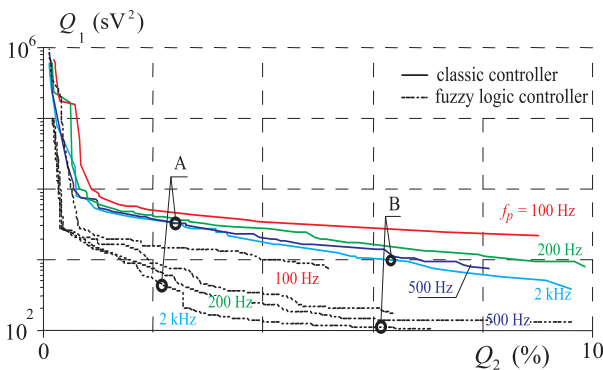


Fig. 7. Compromise sets.

Additionally, for selected points of the compromise set (points A, B — Fig. 7) there were compared the armature voltage waveforms for the classic and fuzzy logic controller measured in a laboratory. The comparison was made for applying the rated load to the generator and the controller sampling frequency equal to 2 kHz. The recorded waveforms are presented in Fig. 8.

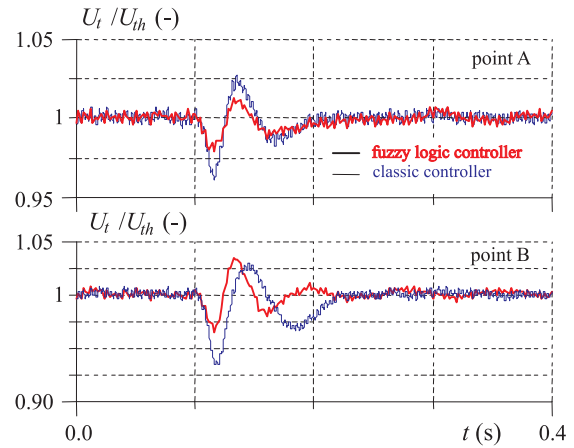


Fig. 8. Waveforms of the stator voltage for points of compromise sets.

The main reason for the change of the generator voltage is the change of its load, while the regulation process depends on the value and type of the load. One of the basic factors influencing undesirably the quality of voltage regulation is the change of the regulation object parameters. That is why the analysis of the influence of changing the load and generator parameters on the compromise sets determined in the polyoptimization process was performed.

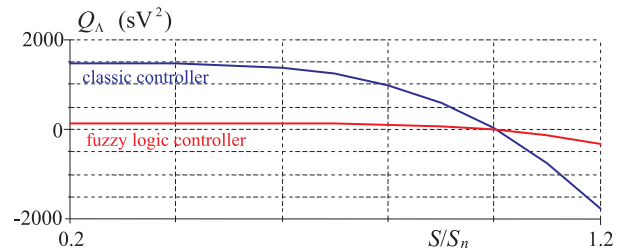


Fig. 9. Dependence of compromise set deformation on the synchronous generator load.

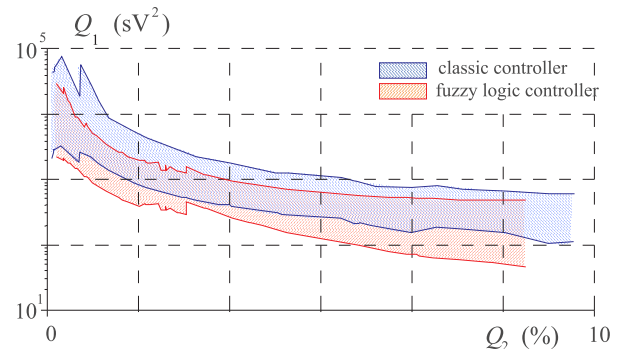


Fig. 10. Bands of compromise set deformation.

The influence of the load change was determined by means of the deformation factor calculated as a function of the load. A deformation factor is a difference  $Q_\Delta = Q - Q^*$  of the area under the output compromise set  $\Lambda$  and the deformed compromise set  $\Lambda^*$  (Fig. 1), where:  $Q = \sum_{i=1}^{i_{\max}-1} (Q_{1(i+1)} - Q_{1(i)}) Q_{2(i)}$ . In  $Q$  there are values

**Table 1.** Rated data of synchronous generators.

TYPE	ECO31 2S/2	ECO31 1S/2	BCA 164G	BCA 162J	BCI 182H	BCI 184F	BCI 162G
Sn (kVA)	40.0	35.0	30.0	29.1	28.0	27.5	25.0
nn (rev/min)	3000	3000	1500	3000	3000	1500	3000
TYPE	BCM 184G	BCI 184E	BCA 162G	ECO3 2L/2	ECO3 1L/2	BCA 164C	BTO3 2L/4
Sn (kVA)	24.8	22.5	21.1	17.0	14.5	1500	13.0
nn (rev/min)	1500	1500	3000	3000	3000	13.5	1500
TYPE	TR2 200/2	BCA 164B	ECO3 2S/2	TR2 130/2	ECO3 1S/2	BTO3 1S/4	ECO3 1S/4
Sn (kVA)	12.5	11.0	9.0	8.0	7.2	7.0	6.0
nn (rev/min)	3000	1500	3000	3000	3000	1500	1500

of the quality factors and in  $Q^*$  there are those taking into account the unfavourable factor. The analysis results for the controllers of sampling frequency equal to 2 kHz are presented in Fig. 9.

The influence of the regulation object parameter changes was determined by means of the bands of the deformed compromise sets whose values were determined when changing the generator parameters. There were analyzed 21 generators of the rated powers given in Table 1. The analysis results for the controllers of sampling frequency equal to 2 kHz in a form of the deformation bands are shown in Fig. 10.

## 5 CONCLUSION

The following conclusions can be drawn from the investigations performed:

- Compromise sets for the fuzzy logic controller are below those for the classic one (see Fig. 7). It means smaller values of the quality factors optimized. So the fuzzy logic controller ensures better possibilities of regulation than the classic one, independently of the sampling frequency.

- Better regulation properties of the fuzzy logic controller are proved by the characteristics shown in Fig. 9. It can be seen that the influence of the load changes on the compromise set for the fuzzy logic controller is considerably smaller.

- Deformation bands (Fig. 10) connected with the generator parameters changes do not much differ for the both controllers. However, the part of the band for the fuzzy logic controller is lower in the objective space, which means that the fuzzy logic controller is more resistant to the regulation object parameter changes.

On the basis of the investigation results presented above one can state that the use of polyoptimization for synthesis of the settings of the synchronous generator voltage regulator makes it possible to readjust better the regulator to the regulation object. The superiority of polyoptimization over one-criterion optimization consists in, first of all, the possibility of simultaneous taking into account different, even contradictory, criteria without necessity of arbitral choice of the criteria weight. The weight is only taken into consideration at the moment of selecting the concrete solution from among the compromise ones.

The additional advantage of polyoptimization is the possibility of performing more profound comparative analysis of different solutions. The comparison of regulation quality on the basis of compromise sets refers to the whole range of the permissive values of the quality factors assumed, not only to one selected point in the whole space of optimal solutions as it is in case of one-criterion optimization.

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