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Synthesis of generator voltage regulator when applying polyoptimisation

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Abstract. The paper presents the method for multicriteria design of a synchronous generator voltage regulator. The results of the voltage regulator polyoptimisation 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 polyoptimisation 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, have resulted in widespread use of autonomous supply sources. The most popular of them is a synchronous generator drived by an internal combustion engine due to its low price, simple construction, long life and resistance to external disturbances. In these units there are applied different stabilising systems in order to keep voltage at the constant level. The systems with phase excitation compaundation are used in sources of lower voltage quality, whereas the electronic systems of automatic regulation are used in those of high output voltage quality.

The increase in stabilisation accuracy of the synchronous generator voltage, especially in transient states, can be achieved by optimisation of regulation system subsets. However, searching for the optimal solution basing on general criteria not closely connected with the regulation object (i.e. integral criteria [1]) not always results in the solution meeting all the given requirements [2]. In the case of high requirements and a number of contradictory criteria, the regulation object can be polyoptimised [2,3].

Polyoptimisation [3] as a generalisation of optimisation has already been used in engineering [3,4]. In a classical approach, the optimisation consists in such changes of the regulation system parameters as to minimise one quality factor. Thus, the optimal solution is a point in the space of permissible values of the quality factor analysed. When performing the polyoptimisation of a regulation system, one searches for a set of optimal solutions minimising the set of factors called aspects [3]. The polyoptimisation 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.

The last stage of polyoptimisation is selecting one solution from among all compromise solutions [3], while the arbitrarily selected polyoptimisation solution is also the optimal solution in the classic approach. It can be proved that it is the extremum of one equivalent quality factor in a form of a weighted sum of the polyoptimisation aspects [3,5].

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

2. General principles of polyoptimisation

As mentioned before, the result of the performed polyoptimisation is the compromise set $\boldsymbol{\Lambda}$, and it is a hypersurface in n-dimensional objective space $\boldsymbol{Q}$ [3], where n is the number of quality factors optimised. The objective space is determined by the permissible values of the quality factors optimised (partial objective functions) Q_i. Since the aspects Q_i are functions of the optimised parameters, the objective space $\boldsymbol{Q}$ is an image of m-dimensional control space $\boldsymbol{X}$ [3], where m is the number of the regulation system parameters optimised.

In the minimisation problem, all such points of the objective space $\left\{\tilde{Q}_1, \tilde{Q}_2, \ldots, \tilde{Q}_n\right\}$ dependent on the control vector $\{\tilde{x}_1, \tilde{x}_2, \ldots, \tilde{x}_m\}$ belong to the compromise set $\boldsymbol{\Lambda}$ for which there is not such a change of the controller parameters x_j, which results in reducing the values of the all quality factors [6–8].

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

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performing the repeated optimisation of all the aspects simultaneously $\boldsymbol{\Lambda}_D$ [3]. The discrete compromise set $\boldsymbol{\Lambda}_D$ consists of the points $\left\{\tilde{Q}'_1, \tilde{Q}'_2, \ldots, \tilde{Q}'_n\right\} \in \boldsymbol{Q}$ and, in the general case, it is the approximation of the compromise set $\boldsymbol{\Lambda}$. Neglecting the inaccuracy of iterative determination of extrema, a genetic algorithm was used for solving the polyoptimisation problem in the presented investigations. It was the algorithm with selection of simultaneous tournaments enabling searching for extremum of many functions [6].

The important problem when analysing regulation systems is to determine the influence of unfavourable factors on the regulation quality. This influence is determined basing on changes of the optimised quality factor values due to the analysed unfavourable factor [1,5]. The similar approach is assumed in the polyoptimisation 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 [2]. For a discrete compromise set the deformation is a change of position of this set points in the objective space analysed. Figure 1 shows the graphical interpretation of the compromise set deformation for 2-dimensional objective space.

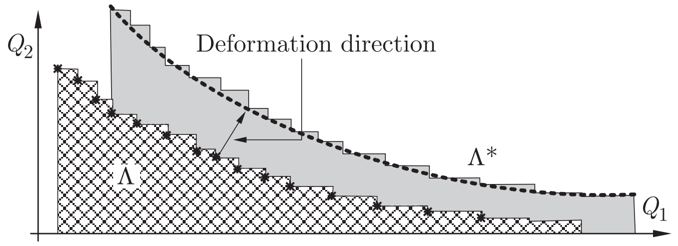

Fig. 1. Compromise set deformation

In order to evaluate the compromise set deformation, there was introduced a coefficient defined as a difference of the area under the output compromise set $\boldsymbol{\Lambda}$ and the deformed compromise set $\boldsymbol{\Lambda}^*$ (Fig. 1):

$$
\begin{aligned}
Q_\Lambda = {} & \sum_{i=1}^{i_{\max}-1} \left(Q_{1(i+1)} - Q_{1(i)}\right) \cdot Q_{2(i)} \\
& - \sum_{i=1}^{i_{\max}-1} \left(Q^*_{1(i+1)} - Q^*_{1(i)}\right) \cdot Q^*_{2(i)},
\end{aligned}
\tag{1}
$$

where: $Q_{1,2(i)}$ – i-th value of the quality factor, $Q^*_{1,2(i)}$ – i-th value of the quality factor when taking into account the unfavourable factor.

3. Mathematical model of a generating unit

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.

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 described by the following matrix equation:

$$
\boldsymbol{U} = \boldsymbol{R} \cdot \boldsymbol{I} + \boldsymbol{L}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{I} + \boldsymbol{\Omega} \cdot \boldsymbol{L} \cdot \boldsymbol{I}, \tag{2}
$$

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

The synchronous generator equivalent diagrams for particular machine axes (Fig. 2) are a circuit representation of Eq. (2); the symbol $\bullet$ denotes that the field magnet circuits are in armature terms.

Resistances and inductances of the equivalent diagrams (Fig. 2) are the parameters of the synchronous generator mathematical model. 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. 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_σ, $L_{f\sigma}$, $L_{td\sigma}$, $L_{kq\sigma}$, were determined at the second stage which was based on analysing 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-exci-

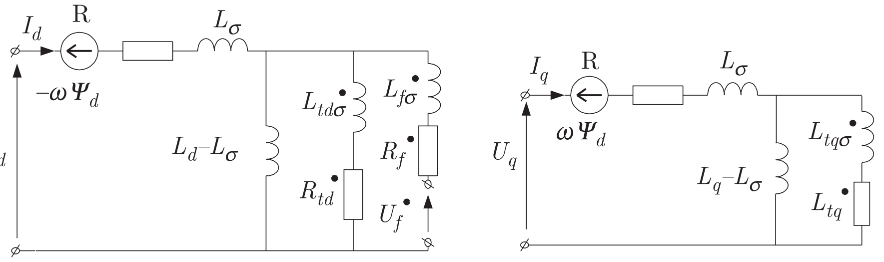

Fig. 2. Equivalent diagram of a synchronous generator

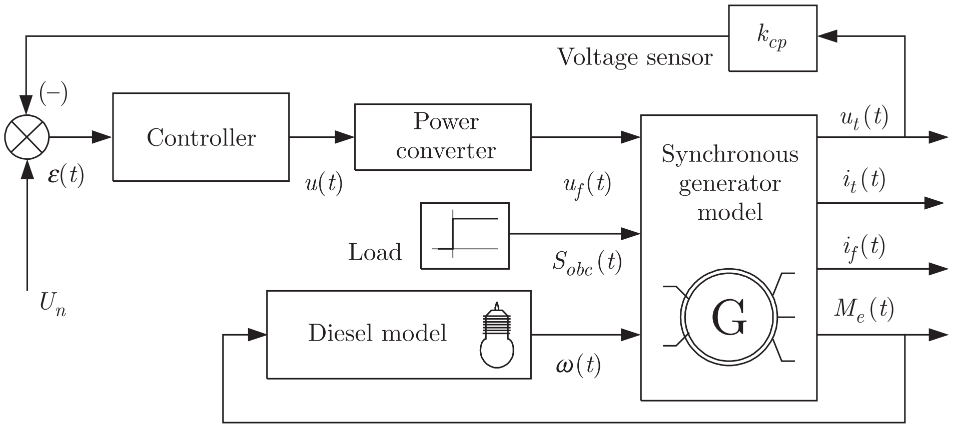

Fig. 3. Block diagram of the generating unit model

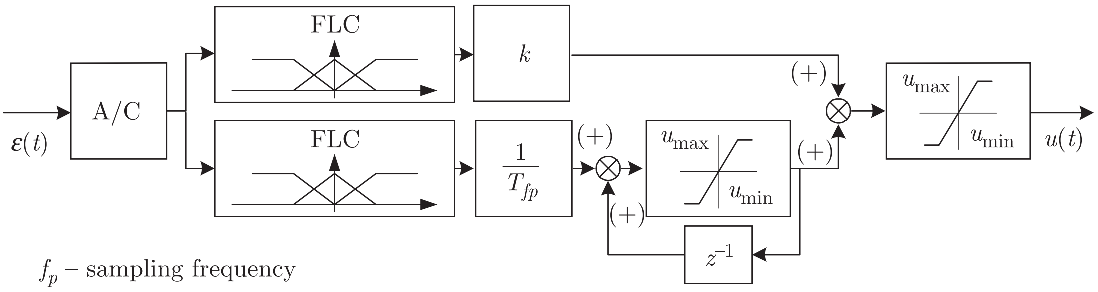

Fig. 4. Block diagram of a fuzzy controller

ted generator, was minimised. The hybrid algorithm applied was a combination of the genetic and Nelder-Mead algorithm [7].

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:

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = T_{\mathrm{m}}(t) - T_{\mathrm{e}}(t), \tag{3}$$

where: ω – angular speed, T_{m} – engine torque, T_e – generator torque.

In order to model the engine torque T_{m}, the partial characteristics of the investigated engine torque were approximated by a polynomial of the third order. Moreover, the analysis of the influence of the delivered fuel quantity ξ on the coefficient values of the polynomial approximating the torque was performed. It was stated that this influence could also be approximated by a polynomial of the third order. For such assumptions, the driving torque of the engine is given by:

$$T_{\mathrm{m}}(\omega,\xi) = \left(\begin{bmatrix} b_{00} & b_{10} & b_{20} & b_{30} \\ b_{01} & b_{11} & b_{21} & b_{31} \\ b_{02} & b_{12} & b_{22} & b_{32} \\ b_{03} & b_{13} & b_{23} & b_{33} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ \xi \\ \xi^2 \\ \xi^3 \end{bmatrix}\right)^{\mathrm{T}} \cdot \begin{bmatrix} 1 \\ \omega \\ \omega^2 \\ \omega^3 \end{bmatrix}, \tag{4}$$

where: $b_{00} \div b_{33}$ – coefficients of the polynomials approximating the driving motor torque.

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

$$\tau_{zp}\frac{\mathrm{d}\xi}{\mathrm{d}t} + \xi = k_{rn}(n_z - n), \tag{5}$$

where: τ_{zp} – time constant of the injection pump inertia, k_{rn} – speed controller amplification, n_z – given speed value, $\xi \in <\xi_{min\ max}>$ where ξ_{min}, ξ_{max} is the limit amount of the delivered fuel.

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

4. Polyoptimisation of the voltage regulator settings

A fuzzy logic PI controller with Takagi-Sugeno-Kanga implication system (TSK-PI) [8] of parallel structure corresponding to a classic PI controller [2,9] 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 [1]. 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 [8]. The structure assumed is poorer and simpler in practical realisation. However, it enables tuning the proportional and integral part independently of each other (as for the classic PI controller).

In order to simplify the optimisation 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 was considered:

IF ε is U THEN u is U,
IF ε is Z THEN u is Z,
IF ε is D THEN u is D.

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

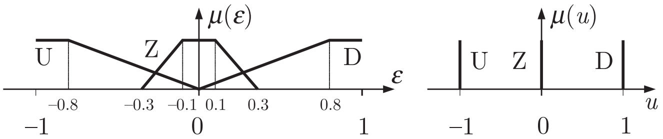

Fig. 5. Membership function of a fuzzy controller

According to the number of requirements imposed, one can select any number of aspects for polyoptimisation. In order to present the results graphically, two quality factors optimised 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}:

$$Q_1 = Q_{\mathrm{ITSE}} = \int_0^{t_r} t \cdot (\varepsilon(t))^2 \, \mathrm{d}t, \tag{6}$$

where: t_r – setting time, ε – control error.

The setting time was defined as a time between the instant of the disturbance occurrence (in the analysed 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].

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

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

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 optimisation 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 optimised.

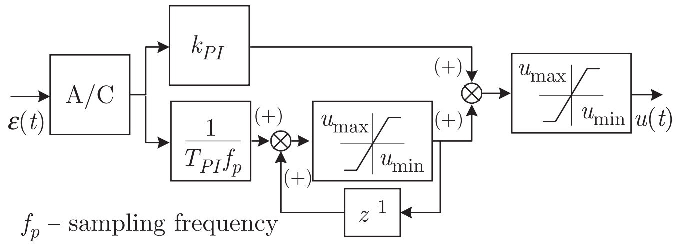

Fig. 6. Block diagram of a classic controller type PI

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

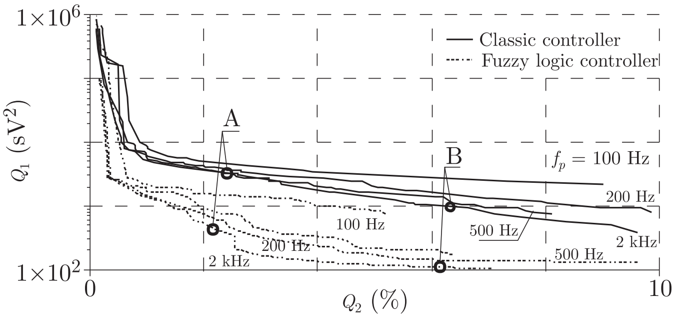

Fig. 7. Compromise sets

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

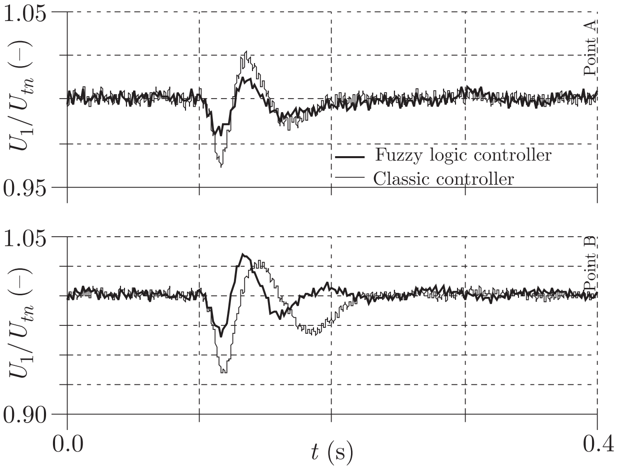

Fig. 8. Waveforms of the stator voltage for points of compromise sets

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

Table 1
Rated data of synchronous generators

	TYP	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
	TYP	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
	TYP	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

regulation is the change of the regulation object parameters. That is why the analysis of the influence of the load and generator parameters changes on the compromise sets determined in the polyoptimisation process was performed.

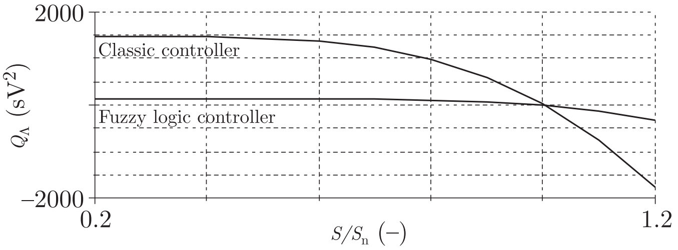

Fig. 9. Dependence of compromise set deformation on the synchronous generator load

The influence of the load change was determined by means of the deformation factor (1) calculated as a function of the load. The analysis results for controllers of the 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 analysed 21 generators of the rated powers given in Table 1. The analysis results for controllers of the sampling frequency equal to 2 kHz in a form of the deformation bands are shown in Fig. 10.

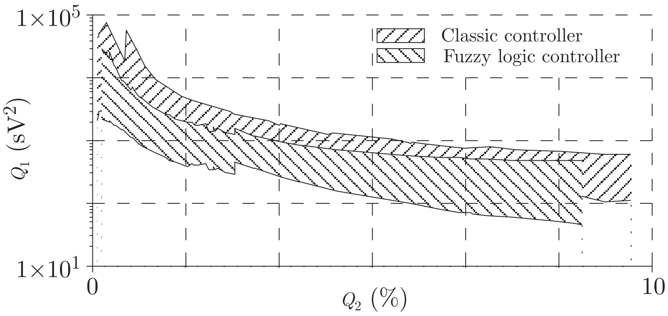

Fig. 10. Bands of compromise set deformation

5. Concluding remarks

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 optimised. 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.

Moreover, it can be stated that the discrete compromise set determined by the genetic algorithm represents the compromise set with the finite accuracy. It is confirmed by the strongly irregular shape of the compromise sets of the investigated controllers (Fig. 7).

On the basis of the investigation results presented above, one can state that the use of polyoptimisation 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 polyoptimisation over one-criterion optimisation 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 polyoptimisation is the possibility of performing more profound comparative analysis of different solutions. The comparison of the regulation quality on the basis of compromise sets refers to the whole range of the permissive values of the aspects assumed, not only to one selected point in the whole space of optimal solutions as it is in case of one-criterion optimisation.

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