Optimal tuning of lead-lag and fuzzy logic power system stabilizers using particle swarm optimization

A.M. El-Zonkoly *, A.A. Khalil, N.M. Ahmied

Arab Academy for Science and Technology, Faculty of Engineering and Technology, Egypt Miami, Alexandria, P.O. 1029, Egypt

Abstract

In this paper, the problem of simultaneous and coordinated tuning of brushless exciter and lead-lag power system stabilizer parameters of a single infinite bus power system is considered. This problem is formulated as an optimization problem, which is solved using particle swarm optimization technique. Also in this paper, the optimal tuning of a fuzzy logic power system stabilizer using particle swarm optimization method is carried out.

Simulation results show the effectiveness of the proposed particle swarm optimization-based lead-lag power system stabilizer and particle swarm optimization-based fuzzy logic power system stabilizer to damp the oscillation of multimachine system and work effectively under variable loading and fault conditions.

Keywords: Particle swarm optimization; Power system control; Lead-lag power system stabilizer; Fuzzy logic power system stabilizer

1. Introduction

Power systems are inherently nonlinear and undergo a wide range of transient conditions, which results in under damped low frequency speed as well as power oscillations that are difficult to control. The generator excitation system maintains generator voltage and controls the reactive power flow using an automatic voltage regulator (AVR) (Cheng, 1997). The role of an AVR is to hold the terminal voltage magnitude of a synchronous generator at a specified level. Hence, the stability of the AVR system would seriously affect the security of the power system. AVR helps to improve the steady-state stability of power systems, but transient stability became a concern for the power system operators. In transient stability the machine is subjected to large impact, usually a fault, which is maintained for a short time and cause a significant reduction in the machine terminal voltage and ability to transfer synchronizing power.

To enhance system damping, the generator is equipped with power system stabilizer (PSS) that provide supplementary feedback stabilizing signal in the excitation system (Anderson & Fouad, 1977; deMello & Concordia, 1969; Sauer & Pai, 1998). The problem of the PSS design is a multimodal optimization problem (i.e., there exists more than one local optimum). Hence, conventional optimization techniques are not suitable for such a problem. Moreover, there is no criterion to decide whether a local solution is also the global solution. Therefore, conventional optimization methods that make use of derivatives and gradients, in general, not able to locate or identify the global optimum.

An overview of the research effort developed in the last decades and also on trends of small-signal studies in power system dynamic analysis are presented in Gibbard et al. (2001), Kundur (1994), EL-Zonkoly (2006), Urdaneta et al. (1991) which discuss the modeling, control techniques and analysis tools available.

Many random search methods, such as genetic algorithm (GA) and simulated annealing (SA) (Feliachi et al., 1988; Xia & Heydt, 1983), have recently received much interest for achieving high efficiency and search global opti-
PSO is one of the optimization techniques and a kind of evolutionary computation technique. The method has been found to be robust in solving problems featuring nonlinearity and non-differentiability, multiple optima, and high dimensionality through adaptation, which is derived from the social-psychological theory. The features of the method are as follows:

1. The method is developed from research on swarm such as fish schooling and bird flocking.
2. It is based on a simple concept. Therefore, the computation time is short and requires few memories (EL-Zonkoly, 2006).
3. It was originally developed for nonlinear optimization problems with continuous variables. It is easily expanded to treat a problem with discrete variables. According to the research results for birds flocking are finding food by flocking.

PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each agent is represented by $XY$ axis position and also the velocity is expressed by $v_x$ (the velocity of $X$ axis) and $v_y$ (the velocity of $Y$ axis). Modification of the agent position is realized by the position and velocity information. Bird flocking optimizes a certain objective function. Each agent knows its best value so far ($pbest$) and its $XY$ position. This information is analogy of personal experiences of each agent. Moreover, each agent knows the best value so far in the group ($gbest$) among $pbest$. This information is analogy of knowledge of how the other agents around them have performed. Namely, each agent tries to modify its position using the following information:

- The current positions ($x, y$),
- The current velocities ($v_x, v_y$),
- The distance between the current position and $pbest$
- The distance between the current position and $gbest$

This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$v_{x}^{t+1} = w v_{x}^{t} + c_{1} rand_{1} \times (pbest_{x} - x_{i}^{t}) + c_{2} rand_{2} \times (gbest_{x} - x_{i}^{t})$$

(1)
where
\[ v^k_i \] velocity of agent \( i \) at iteration \( k \)
\( w \) weighting function
\( c_i \) weighting factor
\( \text{rand} \) random number between 0 and 1
\[ s^k_i \] current position of agent \( i \) at iteration \( k \)
\( \text{pbest}_i \) pbest of agent \( i \)
\( \text{gbest} \) gbest of the group

The following weighting function is usually utilized in (1).
\[
0 < w = \frac{w_{\text{max}} - w_{\text{min}}}{\text{iter}_{\text{max}}} \times \text{iter} \leq 1 \tag{2}
\]
where
\( w_{\text{max}} \) initial weight
\( w_{\text{min}} \) final weight
\( \text{iter}_{\text{max}} \) maximum iteration number
\( \text{iter} \) current iteration number

Using Eqs. (1) and (2) a certain velocity, which gradually gets close to pbest and gbest can be calculated. The current position can be modified by the following equation:
\[
s^{k+1}_i = s^k_i + v^{k+1}_i \tag{3}
\]
Fig. 1 shows a concept of modification of searching point by PSO.

Where
\[ s^k \] current searching point
\[ s^{k+1} \] modified searching point
\[ v^k \] current velocity
\[ v^{k+1} \] modified velocity
\[ v_{\text{pbest}} \] velocity based on pbest
\[ v_{\text{gbest}} \] velocity based on gbest

3. Optimal tuning of lead-lag PSS parameters

The system considered for small-signal performance study is shown in Fig. 2. The synchronous generator considered is equipped with brushless exciter (AC1A) and lead-lag power system stabilizer (LLPSS). The details of the power system with type AC1A excitation system block diagram can be found in Kundur (1994).

The control parameters to be tuned through the optimization algorithm are exciter parameters \( (K_A, T_A, T_B, T_C) \), the lead-lag power system stabilizer parameters \( (T_1, T_2, T_B, K_{\text{STAB}}) \) and terminal voltage transducer parameter \( (T_R) \) as shown in Fig. 3. The inputs to the excitation system are the reference voltage \( V_R \) and the signal from the PSS output \( V_S \). The input to the PSS is the speed deviation \( \Delta \omega \). We will investigate the performance of particle swarm optimization (PSO) technique proposed for tuning excitation system (AC1A) and lead-lag power system stabilizer parameters.

For the linearized system model presented the eigenvalues of the system are evaluated. The proposed method is aiming to search for the optimal parameters set of the AC1A exciter and the lead-lag power system stabilizer so that a comprehensive damping index (CDI) (objective function) can be minimized (Cai & Erlich, 2005).

\[
\text{OF} = \sum_{i=1}^{n} (1 - \zeta_i) \tag{4}
\]
where
\( \text{OF} \) objective function
\( \zeta_i \) the damping ratio
\( n \) the total number of the dominant eigenvalues

The objective of the optimization problem is to maximize the damping ratio as much as possible. The computational flow chart of PSO algorithm is shown in Fig. 4.

The lower and upper limits of the exciter and lead-lag power system stabilizer parameters are given in Table 1.

According to the simulation, the following PSO parameters are used for searching for the LLPSS and exciter parameters:

- The members of each individual are \( (K_A, T_A, T_B, T_C, T_1, T_2, T_B, K_{\text{STAB}}, T_R) \).
- Population size = 50.
- Inertia weight factor \( w \) is set by Eq. (2), where \( w_{\text{max}} = 0.9 \) and \( w_{\text{min}} = 0.4 \).
- Acceleration constant \( c_1 = 2 \) and \( c_2 = 2 \).

The LLPSS and exciter parameters that showed the best solution are summarized in Table 2.

4. Fuzzy logic-based power system stabilizers

The main components of a typical fuzzy logic controller (FLC) include fuzzification, fuzzy inference engine (decision logic), and defuzzification stages. In this paper, power
system model consisting of a synchronous machine connected to infinite bus through a transmission line is used in the simulation studies as shown in Fig. 2. The control signal generated by the fuzzy logic power system stabilizer (FLPSS) is injected as a supplementary stabilizing signal to the AVR system. 

The goal of this application is to stabilize and improve the damping of the synchronous machine. Speed deviation $\Delta \omega$ and active power deviation $\Delta p$ have been selected as the controller inputs. The controller output is then injected into the AVR system.

This configuration implies that the FLC has two input parameters; $K_W$ and $K_P$ and one output parameter $K_U$ as seen in Fig. 5. The selection of these parameters is usually subjective and requires previous knowledge of the fuzzy control variables (input and output signals).

The active power ($\Delta p$), speed deviation ($\Delta \omega$) and the fuzzy output signal ($U$) are divided into seven triangular shape membership functions with full range $[-1$ to $1]$. The membership functions are shown in Fig. 6.

The membership functions related to the speed deviation ($\Delta \omega$), active power deviation ($\Delta p$) are described by [Negative Big (NB), Negative Medium (NM), Negative small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB)], and output signal ($U$) is described by [Output Negative Big (ONB), Output Negative Medium (ONM), Output Zero (OZE), Output Medium (ORM), Output Big (OBB)].

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$K_a$</th>
<th>$T_a$</th>
<th>$T_b$</th>
<th>$T_C$</th>
<th>$K_{STAB}$</th>
<th>$T_W$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_R$</th>
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</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>200</td>
<td>0.01</td>
<td>0.05</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Upper limit</td>
<td>400</td>
<td>0.1</td>
<td>0.1</td>
<td>2</td>
<td>50</td>
<td>2</td>
<td>0.2</td>
<td>0.005</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$K_a$</th>
<th>$T_a$</th>
<th>$T_b$</th>
<th>$T_C$</th>
<th>$K_{STAB}$</th>
<th>$T_W$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal value</td>
<td>200</td>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
<td>50</td>
<td>2</td>
<td>0.2</td>
<td>.005</td>
<td>0.1</td>
</tr>
</tbody>
</table>

(FLPSS) is injected as a supplementary stabilizing signal to the AVR system.

**Fig. 3.** Block diagram representation a synchronous machine with a brushless exciter and LLPSS.

**Fig. 4.** Flowchart of particle swarm optimization process.

**Fig. 5.** Schematic diagram of the FLPSS.

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5. Optimal tuning of fuzzy logic based PSS parameters

Parameter tuning for the FLPSS plays an important role in achieving the controller goals. Previous experience of the controlled system is helpful in selection of the initial values of the FLPSS parameters.

If sufficient information is not available about the controlled system, the selection of suitable FLPSS parameters can become a tedious trial-and-error process. Some efforts have been reported in the literature to automate the tuning of the FLPSS parameters at the design stage to get an optimal or near optimal system performance (EL-Hawary, 1998).

In case of a complete lack of information about the parameters, the search for the best parameters may require a large number of iterations in searching for a proper minimum. Using some practical information about signal levels, it is easy to set an operating range to the FLPSS parameters.

The PSO method is an excellent optimization methodology and a promising approach for solving the optimization problem of FLPSS parameters. Therefore, this study develops the particle swarm optimization-based fuzzy logic power system stabilizer (PSOFLPSS).

The PSO tuning algorithm tries to minimize three system performance indices (PIs). These indices are the system overshoot (OS) and the performance indices $J_1$, $J_2$, given as:

$$OS = \frac{r - y}{r} \times 100\%$$

$$J_1 = \sum e^2$$

$$J_2 = \sum te^2$$

where $r$ is the system reference, $y$ is the system output, $e$ is the system error, and $t$ is the time.

A FLPSS has two input parameters $K_W$, $K_P$ and one output parameter $K_U$. These parameters can be tuned using PSO algorithm which changes the three parameters in overlap loops, and calculates the performance index. The algorithm also detects if one of the parameters degrades the performance indices or leads to instability. The tuning algorithm tries to minimize three system PIs by varying the FLPSS parameter (EL-Hawary, 1998).

The PSO algorithm was mainly utilized to determine the optimal values of three optimal parameters $K_W$, $K_P$ and $K_U$, such that the controlled system could obtain a good output response. We defined the three FLPSS parameters $K_W$, $K_P$ and $K_U$, to compose an individual $K$.

It is worth mentioning that the FLPSS is designed to minimize the power system oscillation after a disturbance so as to improve the stability.

These oscillations are expressed by adding the three system performance indices PIs.

$$W(K) = J_1 + J_2 + OS$$

where

$$W(K)$$ performance criterion

$$K = [K_W, K_P, K_U]$$

In the present study our aim is to minimize the objective function (OF), which is formulated as

$$\min \ OF = \text{abs}(W(K))$$

With the variation of the parameter vector $K$ the OF will also be changed. It aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots.

Table 3
Rule base table for the FLPSS

<table>
<thead>
<tr>
<th>Speed deviation</th>
<th>Active power</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>ONB ONB ONB ONB ONS ONS OSE OZE</td>
</tr>
<tr>
<td>NM</td>
<td>ONB ONB ONS ONS ONS OSE OZE OZE</td>
</tr>
<tr>
<td>NS</td>
<td>ONS ONS ONS ONS OSE OSE OSE OSE</td>
</tr>
<tr>
<td>ZE</td>
<td>ONS ONS OSE OSE OSE OSE OSE OSE</td>
</tr>
<tr>
<td>PS</td>
<td>ONS OSE OSE OSE OSE OSE OSE OSE</td>
</tr>
<tr>
<td>PM</td>
<td>ONS OSE OSE OSE OSE OSE OSE OSE</td>
</tr>
<tr>
<td>PB</td>
<td>OSE OSE OSE OSE OSE OSE OSE OSE</td>
</tr>
</tbody>
</table>

(ONM), output Negative Small (ONS), Output Zero (OZE), Output Positive Small (OPS), Output Positive Medium (OPM), Output Positive Big (OPB)]. Previous experience of the controlled system dynamics is commonly used in the design of the fuzzy control rule base as shown in Table 3.

Table 4
Lower and upper limits of control parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$K_W$</th>
<th>$K_P$</th>
<th>$K_U$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>40</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Upper limit</td>
<td>60</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>
The computational flow chart of PSO algorithm is shown in Fig. 4.

The lower and upper limits of the three controller parameters are given in Table 4.

According to the simulation, the following PSO parameters are used for searching for the FLPSS controller parameters:

- The member of each individual are \( K_W \), \( K_P \) and \( K_U \).
- Population size = 50.
- Inertia weight factor \( w \) is set by Eq. (2) here \( w_{\text{max}} = 0.9 \) and \( w_{\text{min}} = 0.4 \).
- Acceleration constant \( c_1 = 2 \) and \( c_2 = 2 \).

The system with FLPSS and AC1A exciter is shown in Fig. 7. The optimal parameters that showed the best solution are summarized in Table 5.

6. Simulation results

In this section a single-machine-infinite bus system and a multi-machine infinite bus system will be tested after equipped by the proposed PSOLLPPSS and PSOFLPSS. A comparison of the system responses will be done.

6.1. Single machine infinite bus system

In the simulation of the single machine infinite bus system the synchronous machine considered is equipped with brushless excitation (AC1A) system and tested by a unit-step input signal.

Fig. 8 shows the speed deviation of a single machine system with different PSSs. The speed deviation \( (\Delta \omega) \) with the PSOFLPSS and PSOLLPPSS is nearly the same.

The change in the terminal voltage \( (V_t) \) with PSOFLPSS is better than that with PSOLLPPSS with less overshoot and settling time as shown in Fig. 9.

![Fig. 7. Block diagram representation a synchronous machine with a brushless exciter and FLPSS.](image-url)

![Fig. 8. Speed deviation of a single machine system with different PSSs.](image-url)

![Fig. 9. Terminal voltage step response of a single machine power system with different PSSs.](image-url)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( K_W )</th>
<th>( K_P )</th>
<th>( K_U )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal value</td>
<td>59.8</td>
<td>4</td>
<td>1</td>
</tr>
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</table>

Table 5 Optimal values of control parameters
6.2. Multi machine infinite bus system

In this study, a two area interconnected four machine power system shown in Fig. 10 is considered. The system consists of four machines arranged in two areas inter-connected by a weak tie line. The parameters for all generating units, transmission lines, load, and operating conditions are given in Kundur (1994). The system is operating with

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area 1 exporting 400 MW to area 2. The simulation is carried out with the AC1Aexciter and PSOLLPSS or PSOFLPSS inserted in the model of generator 1 (G1). The system is then tested in the following cases:

- Single phase-to-ground fault at bus 8
- Double phase-to-ground fault at bus 8
- Three phase-to-ground at bus 8
- One line out of service
- Load change (+20%).

6.2.1. Single phase-to-ground fault

The speed deviation ($\Delta \omega$) of the system with PSOLLPSS is better than that with PSOFLPSS with less under shoot and settling time as shown in Fig. 11.

The terminal voltage ($V_t$) of machine 1 with PSOLLPSS is better than that with PSOFLPSS with less overshoot but the setting time is nearly the same as shown in Fig. 12.

6.2.2. Double phase-to-ground fault

The speed deviation ($\Delta \omega$) of the system with PSOLLPSS is better than that with PSOFLPSS with less under shoot and less settling time as shown in Fig. 13.

Also in Fig. 14 the terminal voltage ($V_t$) of machine 1 with PSOFLPSS is better than that with PSOFLPSS with less under shoot and settling time nearly the same.
### 6.2.3. Three phase-to-ground fault

The speed deviation ($\Delta \omega$) of the system with PSOLLPS is better than that with PSOFLPSS with less under shoot and settling time as shown in Fig. 15. The terminal voltage ($V_t$) of machine 1 with PSOFLPSS is better than that with PSOFLPSS with less over shoot and settling time as shown in Fig. 16.

### 6.2.4. Line out of service

The speed deviation ($\Delta \omega$) of the system with PSOLLPS is better than that with PSOFLPSS with less under shoot and settling time as shown in Fig. 17. The terminal voltage ($V_t$) of machine 1 with PSOFLPSS and with PSOFLPSS is nearly the same where the settling time and under shoot are nearly the same as shown in Fig. 18.

### 6.2.5. Load change (+20%)

The speed deviation ($\Delta \omega$) of the system with PSOLLPS is better than that with PSOFLPSS with less over shoot and time settling as shown in Fig. 19. The terminal voltage ($V_t$) of machine 1 with PSOFLPSS is better than that with PSOLLPS with less settling time and with over shoot nearly the same as shown in Fig. 20. A comparative study between the time response parameters for different test conditions using PSOFLPSS and PSOFLPSS is presented in Table 6.

### 7. Conclusion

This paper presented a particle swarm optimization method (PSO) as a design method for determining the optimal values of control parameters of the brushless exciter (AC1A), lead-lag power system stabilizer (LLPSS) and fuzzy logic power system stabilizer (FLPSS). Simulation results showed the effectiveness of the proposed PSOFLPSS and PSOFLPSS to damp out the multimachine (interarea) modes of oscillations and work effectively over a wide range of loading conditions and fault conditions.

Furthermore, in multimachine system, the PSOLLPS has given a good response at different types of test conditions considering the speed deviation and small difference between the PSOLLPS and PSOFLPSS in terminal voltage was observed.

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**Table 6**  
Time response parameters for different test conditions using PSOFLPSS and PSOFLPSS

<table>
<thead>
<tr>
<th>Test case</th>
<th>Type of response</th>
<th>PSOPSS Types</th>
<th>Max. over shoot in (pu)</th>
<th>Max. under shoot in (pu)</th>
<th>Peak time in (s)</th>
<th>Settling time in (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Single phase to ground fault</td>
<td>Speed deviation</td>
<td>PSOLLPS 1.60 e-4</td>
<td>-6.99 e-4</td>
<td>0.42</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fig. 11</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Terminal voltage</td>
<td>PSOLLPS 1.4 e-3</td>
<td>-1.1 e-3</td>
<td>0.1</td>
<td>4</td>
<td></td>
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<tr>
<td></td>
<td>Fig. 12</td>
<td></td>
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<td></td>
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<tr>
<td>2-Double phase to ground fault</td>
<td>Speed deviation</td>
<td>PSOLLPS 2.38 e-4</td>
<td>-7.81 e-4</td>
<td>0.45</td>
<td>5</td>
<td></td>
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<tr>
<td></td>
<td>Fig. 13</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Terminal voltage</td>
<td>PSOLLPS 1.3 e-3</td>
<td>-1 e-3</td>
<td>0.9</td>
<td>4</td>
<td></td>
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<td></td>
<td>Fig. 14</td>
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<tr>
<td>3-Three phase to ground fault</td>
<td>Speed deviation</td>
<td>PSOLLPS 6 e-4</td>
<td>-6.45 e-3</td>
<td>0.87</td>
<td>4.5</td>
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<tr>
<td></td>
<td>Terminal voltage</td>
<td>PSOLLPS 4.3 e-3</td>
<td>-6.1 e-3</td>
<td>1.33</td>
<td>6.0</td>
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<td></td>
<td>Fig. 16</td>
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<tr>
<td>4-Line out of Service</td>
<td>Speed deviation</td>
<td>PSOLLPS 5.5 e-3</td>
<td>-3.2 e-2</td>
<td>2.2</td>
<td>8.5</td>
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<td></td>
<td>Fig. 17</td>
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<tr>
<td></td>
<td>Terminal voltage</td>
<td>PSOLLPS 5 e-3</td>
<td>-3.4 e-2</td>
<td>2.3</td>
<td>9.0</td>
<td></td>
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<td></td>
<td>Fig. 18</td>
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<tr>
<td>5-Load change (+20%)</td>
<td>Speed deviation</td>
<td>PSOLLPS 6 e-3</td>
<td>-6.7 e-3</td>
<td>0.12</td>
<td>11</td>
<td></td>
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<td></td>
<td>Fig. 19</td>
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<tr>
<td></td>
<td>Terminal voltage</td>
<td>PSOLLPS 4 e-3</td>
<td>-6.6 e-3</td>
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<td>Fig. 20</td>
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**References**


