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Review

A Comprehensive Review of Power System Stabilizers

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Abstract: This paper presents a current literature review (from the years 2017–2022) on issues related to the application of power system stabilizers (PSSs) for damping electromechanical swings in power systems (PSs). After the initial selection of papers found in the databases used, over 600 publications were qualified for this review, of which 216 were subjected to detailed analysis. In the review, issues related to the following problems are described: applications of classic PSSs, applications of new stabilizer structures based on new algorithms (including artificial intelligence), development of new methods for tuning PSSs, and operation of PSSs in PSs with high power generation by renewable sources. Describing individual papers, the research methods used by the authors (simulations, measurement methods, and a combination of both) are specified, attention is paid to the waveforms presented in the papers, and reference is made to the types of PSs in which PSSs (large multimachine, reflecting real systems, smaller standard multimachine New-England type, and simplest single-machine) operate. The tables contain detailed comments on the selected papers. The final part of the review presents general comments on the analyzed papers and guidelines for future PS stability studies.

Keywords: power systems; power system stabilizers; optimization

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1. Introduction

A power system (PS) is a complex system consisting of devices for the generation, transmission, distribution, processing, and consumption of electric energy. The purpose of PS operation is to ensure an uninterrupted supply of electricity of appropriate voltage and frequency while minimizing the costs of its generation and transmission.

A power system is subject to constant changes resulting from many reasons. There is a permanent transient state in PSs. The classification of PS transients can be performed based on various criteria. One of them is the criterion resulting from the type of changing physical quantities. Electromagnetic, electromechanical, and thermal transient states are usually distinguished (Figure 1). This division is also related to the rates of change (i.e., the time over which these changes take place) of given quantities.

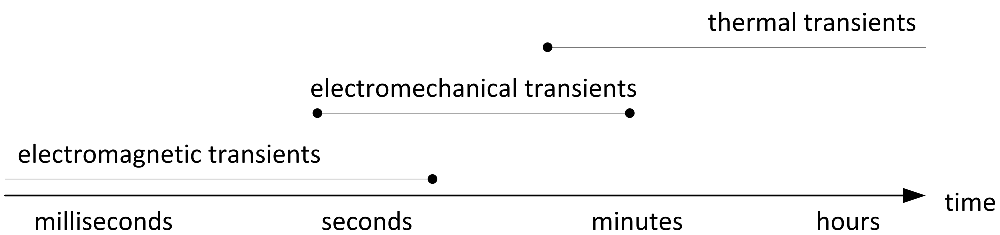


Figure 1. Classification of transient states.

Electromagnetic transient states are associated with fast changes in magnetic and electrical quantities, including, among others, magnetic fluxes, currents, and voltages. They occur in the shortest time, usually not longer than a few seconds, after the phenomenon that cause them (e.g., short circuits).

Electromechanical transient states refer to situations in which electrical quantities (currents and voltages) and mechanical quantities (mechanical powers and rotational speeds of electrical machines) change simultaneously. The concept of electromechanical swings is inextricably linked with electromechanical transient states in systems with synchronous machines. This concept is defined as oscillating changes in the position of a rotor with respect to the stator. In electromechanical transient states, changes also take place after stabilization of the electromagnetic quantities. The duration of electromechanical transients is from several to several dozen seconds.

Thermal transient states associated with changes in the temperature of the elements included in a PS are the last group of transients. Thermal phenomena are usually the slowest. Their duration ranges from tens of seconds to minutes or hours. Visible changes in values in thermal transient states usually begin after the disappearance of electromechanical changes.

It should be emphasized that all the above-mentioned transient states are interrelated—one occurring transient state entails the occurrence of another state being slower.

Regardless of the type of transient, a state threatening the security of energy supply, i.e., a failure, may arise in a PS. Therefore, properly designed systems are used in PSs to eliminate possible failures or to minimize their effects. Among the devices eliminating threats in electromagnetic transient states, one should mention electric power protection automatics. Devices operating during electromechanical transient states include devices that stabilize PS operation. The elimination of unfavorable temperature changes in PSs takes place thanks to appropriate heating or cooling devices and thermal protections.

This review concerns devices whose operation is aimed at stabilizing PS operation in electromechanical transient states. It should be emphasized that the literature on the analysis of electromechanical transient states and the related stability of PSs [1–4] is exceptionally wide. Research is conducted all the time. Recently, the interest in this topic has been increasing as new elements, including renewable sources and energy storage that influence these transients, have been installed in PSs. The expansion of a PS causes a number of new stability problems that scientists try to solve in various ways, including the use of appropriate devices and control systems, the most popular of which are power system stabilizers (PSSs).

As part of the literature review, several databases (websites) containing scientific publications were searched. Due to the very rich literature, the scope of the search was limited to 2017–2022. For example, after entering the phrase "power system stabilizers" in the Elsevier database (Science Direct), the search system gave 18.327 results (2023—25, 2022—3544, 2021—3780, 2020—3106, 2019—2831, 2018—2640, and 2017—2401 results). After the preliminary selection of papers found in the databases, more than 600 publications were qualified for this review, of which 216 papers were analyzed in more detail.

It should be borne in mind that the papers selected for discussion were usually multithreaded. For example, they relate to the use of artificial intelligence methods and distributed energy sources. Consequently, the division assumed in the paper should be treated as a subjective choice of the authors. Nevertheless, the authors tried to divide them into individual thematic groups in such a way that the papers classified to a given area reflected the trends observed in the literature.

This review consists of an introduction, a conclusion, and six sections in which the issues from various subject groups are discussed. The first group, described in Section 2, includes classic PSS solutions. In Section 3, stabilizing systems based on artificial intelligence are discussed. Section 4 deals with the issues related to modern automation algorithms and currently installed PS elements. Section 5 focuses on the discussion of papers on electromechanical transient states in PSs with renewable energy sources (RESs) installed. New methods of tuning systems for the stabilization of PS operation are described in Section 6. The discussion is contained in Section 7. It presents a critical look at the possibility of practical and common use of advanced solutions for PSSs in power engineering. Reference is also made to frequently overlooked but important areas of research, such as the place of installation of power-stabilizing systems in PSs and the uncertainties of parameters and measurement tests that allow for final verification of the obtained results. As part of the summary, the found review papers on the issues discussed are also presented. The information contained in individual sections is supplemented with tables in Appendix A.

Moreover, in the sections, there is no division of swings into local and inter-area because, in most cases, the investigations were based on simulations of test systems without explicit reference to the practical application of the discussed case. With this approach, the type of swing actually does not matter. In the case of papers for which it is relevant, information about the type of swing is provided in the table (with detailed notes) or in the text of the given section.

As part of the review research, an initial selection of papers available in the most popular digital libraries of scientific publishing houses and organizations was carried out. As a result, a representative group of publications was selected. The authors of this review, for the purpose of qualitative analysis of the selected papers, developed a number of criteria according to which these papers were evaluated. This assessment was used for the discussion and critical analysis in Section 7. As a consequence, general conclusions were drawn and guidelines for further research, in particular related to the possibility of the practical use of solutions described in the literature, were adopted.

2. Classic Solutions for PSSs

Ensuring PS stability is one of the basic technical problems of power engineering. It should take place at the design and construction (expansion) stage of a system. Control systems such as power system stabilizers are only additional elements, i.e., means of improving stability and mitigating transient states. Synchronous generators, as the primary power sources in PSs, are equipped with damping circuits generating relatively high electromagnetic damping torques. However, the operation of excitation systems, especially fast static ones, can reduce the values of these torques, adversely affecting the waveforms of electromechanical transient states. This unfavorable influence of voltage regulation systems can be reduced, among others, by the use of additional, regulating elements called PSSs— in this section, understood as classic systems [2].

It should be emphasized that the use of classic power system stabilizers in the modern digital voltage regulators of synchronous generators does not require large financial outlays (a PSS is implemented as an additional fragment of the voltage regulator program code) compared to other solutions improving PS stability (e.g., FACTS systems). It is worth noting that the improvement in the damping of electromechanical transient states of PSs thanks to the use of PSSs installed in excitation systems deteriorates the quality of voltage regulation [2,4–7]. Nevertheless, the effects of classic PSSs can be comparable to the effects of other systems, provided that they are properly selected (in terms of structure and parameters). Therefore, the use and scientific research of classic PSSs are still justified.

Currently, various types of stabilizers are used in practice, from the simplest single-input to complex, broadband, multi-input ones. Single-input stabilizers (e.g., PSS1A-type) are simple in construction and tuning but have their drawbacks (e.g., a PSS with one input from rotational speed when the speed is measured only in one place of the generator shaft can amplify the torsional vibrations of the generating unit). These disadvantages can be eliminated by using multi-input PSSs. Then, various causes of electromechanical swings can be eliminated. However, tuning PSSs then becomes more difficult. It is also worth emphasizing that incorrectly selected PSS parameters may worsen, not improve, the course of electromechanical transients (i.e., strengthen the swings)—papers on the correct tuning of PSSs are discussed, among others, in Section 6.

The authors of this paper included 42 items in the group of papers discussing the scientific issues of classic power system stabilizers. Among them, four subgroups differing in the subject matter discussed can be distinguished. The first subgroup, consisting of five papers, concerns research on general issues, such as changes in the structure of PSs, problems of PS stabilization, principles of simplifying mathematical models (used in simulation investigations), and practical tuning methods. This subgroup includes papers [8–12], while [12] (despite the fact that it was published outside the analyzed period of time) is a selection from broader investigations by one of the co-authors of this review concerning the whole issues of PSS application in PSs, including optimization of parameters and locations of PSS installation. The second, most numerous subgroup is papers in which the technical aspects of classic PSSs are discussed, including their tuning, interaction with other PS elements, modifications of PSS structures, and the place of installation of PS-stabilizing systems. This subgroup includes 26 papers [13–38]. The third subgroup consists of three papers related to the interaction of PSs, renewable sources, and new PS elements [39–41]. These are only sample papers, and a wider selection of research on this topic can be found in Sections 4 and 5. The last, fourth subgroup consists of eight papers [42–49]. The investigations described in them concern an important but often omitted problem of mathematical modeling, particularly the parameter estimation of mathematical models of PS elements. According to the authors of one of the papers [43], simulation studies are necessary to determine the best practices in the field of planning and operation of power systems. They provide insight into how its elements behave in transients. Therefore, it is important that the mathematical models representing the existing infrastructure, particularly of power plants (generating units), are reliable, i.e., they reflect reality sufficiently. Reliable mathematical models are necessary for such activities as protection coordination, design and tuning of power system stabilizers, accurate tuning of underexcitation and overexcitation limiters, etc. Therefore, although indirectly, research on mathematical modeling (parameter estimation of mathematical models of PS elements) is an integral part of issues related to PS stability and, in particular, the technical issues related to the use of PSSs.

The papers included in the last subgroup are not taken into account in the further part of this section—they are not included in the summaries or in Table 1, which contains detailed comments on the selected papers.

Table 1. Detailed comments on selected papers analyzed in Section 2.

Detailed Comments	Paper
A paper on general issues related to PS stability. PSs with different, complex structures of power network were analyzed. Particular attention was paid to the problems of PS management (its control) resulting from current changes in the power network. Only 52 items were referred to in the literature list, but the paper should be treated as a literature review in the analyzed topic. The authors, through a critical analysis of the existing solutions, presented a possible transition path from the current, hierarchical control system (PS) to a new structure that, according to the authors, supports the decarbonization of electricity generation.	[8]
In this paper, the authors presented the problems occurring in PSs related to the relatively high power generation by photovoltaic (PV) sources and proposed solutions that could help reduce these problems.	[9]
This paper presents the current problem regarding the increase in the number of electricity sources characterized by stochastic changes in the generated power, which result in stochastic changes in frequency in PSs. The authors proposed new methods of PS modeling, taking into account distributed generation with stochastic properties.	[10]
This paper describes the problems related to PSSs installed in an Indian PS. The authors presented many interesting technical problems.	[11]
In this paper, the authors proposed the use of properly tuned (e.g., optimized by simultaneous tuning of many stabilizers) classic PSSs to damp inter-area oscillations as an alternative to expensive FACTS systems.	[13]

Table 1. *Cont.*

Detailed Comments	Paper
This paper, through a thorough analysis of the hydraulic-mechanical part of a generator drive system, presents a justification for the need to take into account turbine model in electromechanical tests of transients, as well as in the optimization of PSS parameters and voltage regulators (AVRs). However, the authors in their research unfortunately used a simplified generator and network model (SMIB), which might lead to a lack of reliability of the obtained results.	[14]
The authors presented a solution to the problem of limiting the allowable gain in a PSS main circuit resulting from the provisions of the "guide for setting test of power system stabilizer" of China. By modifying the structure of a PSS, improvement in the damping of inter-area oscillations was achieved.	[15]
In this paper, an interesting modification of the structure of a lead-lag single-entry power system stabilizer improving its properties was presented.	[16]
The paper concerns research related to the first nuclear power plant in Egypt (El-Dabaa). The authors, apart from specifying the stabilizer for the actual generating unit, presented the parameters of a mathematical model of this unit.	[17]
The authors presented research leading to the elimination of low-frequency swings in PSs. The influence of several PSSs installed in Spanish power plants on the damping of inter-area swings (0.15 Hz) occurring in the European system was analyzed. The appendix to the paper provides the parameters of the mathematical models used.	[24]
In this paper, an analysis of the event (disturbance) that took place in Canada on 22 May 2018 is presented. This event caused power oscillations in a PS. The PSS-E program from Siemens was used for the simulation tests.	[25]
In this paper, research on the Iraqi Super Grid is presented. Unfortunately, despite being a case study, only the results for a 14-machine test system (South-East Australian) were included.	[26]
The authors of this paper used Power System Computer-Aided Design software (PSCAD) to carry out simulation tests. The Tehri Hydropower Plant (HPP) and Koteshwar HPP high-power hydropower plants in India, part of the Tehri Hydro Power Complex with an installed capacity of 2400 MW, were investigated.	[27]
This paper concerns a technical problem that occurs in real control systems, i.e., the influence of the PSS dead zone on the operation of a stabilizer and the principles of design of this dead zone.	[28]
The authors, using research on transient states in PSs, presented an interesting alternative to Matlab, i.e., the SCILAB program.	[31]
The paper presents, among others, measurements made at the Power System Stability Laboratory of TU Sofia. The authors presented a lot of results of simulation tests obtained with the use of ready-made models from the Matlab toolbox.	[32]
The authors presented measurements and analyses of the operation of a power plant in Inner Mongolia (China) under the load of two generators at 70% and 30% of the rated power.	[34]
Using stability studies, the authors presented the possibilities of the Power World Simulator program for the investigation of transients in PSs.	[35]
In this paper, an analysis of the influence of excitation systems on electromechanical transients is presented. Two types of excitation systems, DC1A and ST1A [50], were tested.	[36]

Table 1. *Cont.*

Detailed Comments	Paper
This paper presents a two-input, "single-band" stabilizer of the PSS3B type rarely described in the literature. According to the author, the paper aimed to fill the gap in the PSS3B's ability to provide good phase compensation for a wide frequency range. Two PS models, three- and two- machine ones, were analyzed. The summary presented conclusions and technical recommendations, e.g., regarding the advantages and disadvantages of the PSS3B stabilizer, including the possibility of damping torsional oscillations.	[37]
Using DigSILENT Power Factory software, the authors presented the risks associated with increase in PS power generation by wind turbines.	[39]
Using the ETAP program, the authors presented the problem of transients occurring in a PS with connected generating units, including wind, photovoltaic, and Diesel engine.	[40]
The authors present studies on the actual fragment of the large PS (Yunnan - China Southern) containing HVDC links. The analyzed PS fragment contains as many as 7 HVDC links. The paper presents a solution to the described problems.	[41]

In the papers included in the group discussed in this section, the basic method of research (as in most of the analyzed papers throughout this review) was computer simulation. As the only test method, simulation was used by the authors of 29 papers [9,10,12–24,26–31,33,35–40,49]. Measurement methods (alone or in combination with simulation studies) were used by the authors of only six papers [11,25,32,34,41,42]. The study detailed in [8] was excluded from the list of methods due to the review nature of the research described in it.

When analyzing the types of power system models used in research, it should be stated that authors use a large variety of test systems and often their own systems, including those mapping real systems (this also applies to the simplest single machine infinity bus /SMIB/ system, which can be created for a specific, real case [34]).

Among the standard test systems, the most often used was the SMIB system, which was applied by the authors of 10 papers [14,20,21,29–34,38]. The authors also used other standard systems, including 20-machine Nordic (for example, in [9,42]), four-machine two-area (hereinafter called 4M2A) [13,16,18,19,23,49], ten-machine New England [10], and three-machine WSCC [36] systems.

There was also a great diversity in the tested types of power system stabilizers. However, the most frequently described type of stabilizers was the single-input lead-lag PSS (in various versions, including PSS1A), which was tested by the authors of 19 papers [13–16,18–22,25,26,28,31,33,35,36,40,44,49] (which should not come as a surprise, as it is a stabilizer that is often used in practice due to its relatively simple tuning). Among other types of PSSs tested in the publications described, it is worth mentioning the PSS2A stabilizer and its variants tested, among others, by the authors of [21,24,29,34,41] and the PSS3B stabilizer tested, e.g., by the authors of [27,30,37].

Taking into account the number and type of the analyzed waveforms, it can be concluded that, in the papers included in first group (classic PSS solutions), the greatest variety in analyzed waveforms occurred. One waveform only was shown in eight papers [10–13,19,21,34,40,49], and most often, it was the angular speed of the rotor or its change (deviation). The remaining papers presented two or more waveforms, but some [18,20,25,26,29,31,32,36,38] did not present generator stator voltage waveforms (terminal voltage). The waveform of this voltage, as a quantity not directly related to electromechanical swings, usually has a different character than waveforms of electromechanical quantities (angular speeds of rotors, power angles, and instantaneous power of generators). Therefore, it is worth analyzing the above-mentioned waveforms when examining the effectiveness of PSSs.

Table 1 presents detailed comments on the selected papers analyzed in this section.

3. Artificial-Intelligence-Based PSSs

Techniques and methods based on artificial intelligence have been present in scientific research for many years. They are also constantly being developed, both on the theoretical and application level. In case of complex, nonlinear objects that behave unpredictably, artificial intelligence methods are willingly used due to their high potential. A power system is such an object. Therefore, it is not surprising that there are many scientific papers describing the use of artificial intelligence methods in PS control. Nevertheless, the number of these papers is much smaller than those related to PS stabilization in which the uses of techniques other than artificial intelligence are presented (cf. tables in other sections of this review).

In the analyzed papers related to electromechanical transients, three techniques of artificial intelligence are discussed, i.e., artificial neural networks, fuzzy logic, and their combination, i.e., neural-fuzzy systems. Recently, however, there has been no greater interest in expert systems used as an element of systems stabilizing PS operation.

A total of 33 papers that present research on the use of artificial intelligence to stabilize PS operation in electromechanical transients were selected for the detailed discussion. In all the cases, artificial intelligence methods are presented as an alternative to classic solutions (i.e., those in which artificial intelligence methods are not used). Among the papers, one can distinguish those in which the analyzed PSs contain more and more numerous renewable sources (wind power plants and photovoltaic systems), as well as power electronic devices controlling system operation (e.g., static reactive power compensators STATCOM) [51–54]. It is worth emphasizing that, in only one case out of all 33 papers, the authors referred to a specific technical problem in a real PS. This paper was about the PSS for the Al Sarir West Power Plant (SWPP) in Libya [55]. Unfortunately, also in this case, the paper had rather the character of a theoretical analysis.

The authors of the discussed papers described various types of regulation systems based on the artificial intelligence technique to stabilize PSs. Due to the variety of solutions, it was very difficult to distinguish subgroups relating to specific regulation techniques. Nevertheless, among the analyzed papers, one can distinguish papers on sliding control [56–58], PID controllers [54,59–63], and adaptive systems [50,63–65].

All the papers discussed in this section (including a previously cited paper [55]) presented computer simulation as the primary research tool.

The authors of the analyzed papers mostly used only one test power system in their research. There were 23 such papers. Among them, in fourteen papers, a system consisting of one generator and an infinite bus SMIB was described [51,55,60,61,64–73]. This system was sometimes extended with additional elements, such as, for example, reactive power compensation systems. In seven papers, the research concerned a two-area system with four machines [52,54,59,63,74–76]. In the remaining two papers [62,77] the uses of different systems were presented. Transient waveforms occurring in two different systems were investigated in nine cases. In these papers, most often (seven times) the simplest SMIB system and the 4M2A system were analyzed [53,56,57,78–81]. However, in two papers, two other systems were analyzed [58,82]. Only in one paper [83], were three test systems analyzed, and on this basis, conclusions were drawn about the possibility of stabilizing PS operation.

When analyzing the number of the waveforms presented in the papers, it was found that, in almost half of the papers (i.e., 15), only one transient waveform of the examined PS was presented. In ten of these papers, the waveforms of the angular speed, its changes (deviations), or frequency were shown. The waveforms of the power angle or changes in this angle were presented in the remaining five papers.

The authors of twelve publications present two waveforms. Three or more waveforms were shown in six papers. The generator terminal voltage waveforms (not being an electromechanical quantity) were presented in seven cases.

Table 2 summarizes the discussion comments concerning the selected papers.

Table 2. Detailed comments on selected papers analyzed in Section 3.

Detailed Comments	Paper
The introduction to this paper contains a very extensive literature review containing 42 items.	[54]
One of the goals of the tuning described in the paper was to minimize the overshoot and maximize the undershoot of the angular speed deviation. In this context, it seems that there was lack of in-depth analysis of the impact of such a criterion on the generator terminal voltage waveforms.	[55]
When examining the transients in a SMIB system, the authors assumed, among others, an unusual disturbance in the form of a load power change of 0.2 p.u.	[64]
The authors emphasized the practical importance of classic PSSs (i.e., not based on artificial intelligence) resulting from their simpler structure and ease of tuning.	[78]
It is worth comparing these two selected papers due to the very similar, partially repeated investigations. One paper [68] is from the conference taking place on 30 April–3 May 2017 (date added to IEEE Xplore: 15 June 2017), while the other paper [67] is from the conference on 21–24 May 2017 (date added to IEEE Xplore: 7 August 2017).	[67,68]
In Section 2 of this paper, the concept of modeling uncertainty used in creating the model was introduced. To identify the system, a test signal introduced as a reference value to the generator excitation system was used. The signal was a square wave with a relatively large amplitude of ±0.2 p.u.	[76]
The authors of this paper presented research in which PS electromechanical transients caused, among others, by asymmetrical short circuits, i.e., single-phase fault-to-ground, were analyzed. Nevertheless, the applied mathematical model did not take into account asymmetric states and did not assume subtransient symmetry (Xd″ for all three machines was different than Xq″—a more extensive description of the model used is presented in [47] from the reference list of this paper).	[77]
The paper provides a broad review of the literature on various ways of stabilizing PSs.	[79]
In the introduction to this paper, the authors presented a list of selected failures caused by power swings in PSs.	[83]

4. Modern Control Systems in PSs

The constantly developing theory of automatic control causes new control systems to be used to control the processes taking place in complex systems, including PSs. Attempts to adapt new theories have been reflected in numerous scientific publications. A similar effect is achieved by the constant development of power electronic converter systems, thanks to which it becomes possible to control voltage, power flow, etc. in PSs.

Some authors of publications have tried to use new control systems as elements to improve waveforms in the electromechanical transients in PSs. It should be emphasized that some of these systems have been a permanent element of PSs for some time (e.g., reactive power compensation systems). Nevertheless, the development works on them are still carried out on a large scale, and new possibilities of these systems are still considered.

In this review, the papers related to modern control systems include 50 items, with the proviso that some of the investigations presented in the papers were difficult to divide into two separate categories, i.e., modern control systems (described in this section) and PSS-tuning methods (described in Section 6). This problem results from the fact that the description of new control systems is often combined with the description of a tuning method.

All the papers analyzed in this section are divided into three thematic blocks. The first group includes papers in which the main scientific problem under consideration is a stabilizer, a control system, or more precisely, a regulator used to damp the waveforms of selected quantities (e.g., terminal voltage, instantaneous power, or angular speed of synchronous generators) during electromechanical transients. This group consists of 24 papers [7,84–106]. The second group contains papers also on control systems, but only those that use a distributed measurement technique, including systems based on the phasor measurement unit (PMU). A total of 10 papers in this group are analyzed [107–116]. The last group consists of 15 papers on the use of power electronic power converters, including FACTS devices, for PS stabilization [80,117–131]. It should be emphasized that the last group also includes publications on battery energy storage systems (BESSs) equipped with power electronics systems. The papers of [119,126] may be an example of such publications.

The second, natural, applied division criterion is the technology used in the control systems. However, in the publications under consideration, it was difficult to separate groups concerning various issues. This was due to a large number of publications in which the authors' solutions were described. It could only be considered that a part of the publications contained reference to lead-lag stabilizers known from the literature or their modifications [108,112,120,121,124,126,128–131]. Another type of system described in the publications under consideration was fractional order systems [92,98,101,105,115]. Papers containing solutions based on a PSS4B stabilizer or its variants [93,95,100,104,106] could also be distinguished. The PSS4B stabilizer is a well-known solution but is relatively rarely used due to the large number of its parameters.

Computer simulation was the basic tool for the analyses described in this section. It was used by the authors of as many as 47 out of 50 selected papers as the only method. Among all the papers, it is worth mentioning the three papers in which a specific technical problem was solved using simulation techniques [87,95,99]. Only in three publications, in order to solve the problem or confirm the obtained results apart from simulation, were measurement methods used on real objects or in a laboratory [7,86,100].

Simulation investigations on modern control systems in PSs, similarly as in other groups of problems, were most often performed using only test systems and only in exceptional cases with the use of a mathematical model of a real PS or fragment, as was the case in one publication [88]. Among the papers based on the analysis of test systems, only one PS was tested in forty-one cases, in particular: three-machine systems (including WSCC) [117,120,121,123,128], four-machine 4M2O [90,94,97,101,106,109,110,114,115,119,132] systems, and larger (e.g., New England 10-machine system or extended version with 16 machines) [108,111–113,119]. In the other 16 cases, only SMIB systems were analyzed [80,84,89,91–93,96,98,99,102,103,105,118,122,127,130]. Only in nine papers were two different PSs used for testing [85,87,88,95,104,107,116,124,125].

The results of the simulation tests and measurements presented in the papers were usually the waveforms of various quantities in the PSs. Only one selected waveform was presented in seventeen papers: rotor angular speed, its increment (deviation) or frequency [84,87,96,101,105,107,108,114,116,120–122,126,130], or instantaneous power [95,107,112]. Two different waveforms were analyzed in twelve papers, with three or more waveforms in twenty-one publications.

Terminal voltage (as a quantity not directly related to electromechanical swings), along with other waveforms, was presented in sixteen papers, which was almost half of the papers with more than one analyzed waveform [83,85,86,88,91,92,97–100,109,110,117,119,127,128]. Only one of the analyzed papers did not present any waveforms [93]. The obtained results referred only to the analysis of the eigenvalues of the system state matrix.

The detailed comments concerning the selected papers related to modern control systems operating in PSs are given in Table 3.

Table 3. Detailed comments on selected papers analyzed in Section 4.

Detailed Comments	Paper
In the introduction to this paper, an extensive literature review was carried out in which as many as 49 items were analyzed. In the research, a step change in the reference voltage from 0.9 to 0.8 p.u was used as the cause of the transient. When analyzing the recorded waveforms during laboratory tests, a typical phenomenon could be noticed: improvement in the generator power waveform caused by the operation of PSS deteriorated the voltage waveform (Figure 5, page 220).	[7]
This paper presents a PSS based on the use of artificial intelligence methods as a stabilizer for a static synchronous series compensator (SSSC). This is a good example illustrating the fact that the use of a PSS in a PS is no longer reserved only for the excitation systems of synchronous generators. Such a situation has been forced by changes in PS structure and, in particular, the connection of renewable sources that adversely affect the stability of a system.	[80]
This paper presents comparative studies of the effectiveness of the operation of many different types of PSSs working in SMIBs.	[84]
In this paper, a stabilizer using Park real-time transformation was proposed. The obtained results were experimentally verified using a synchronous generator with an apparent power of 83 kVA.	[86]
In this paper, a specific problem observed in a real PS is presented. "In April 2016, when an asynchronous connection test was performed to connect the Yunnan power grid to China Southern Power Grid (main grid), a ultra-low-frequency oscillations arose in the Yunnan power grid with an oscillation frequency of 0.05 Hz and amplitude of 0.1 Hz." (page 1) The authors modeled this case and proposed a solution to the problem.	[87]
In simulation studies, the authors analyzed changes untypical for real systems causing the transient state in a PS, namely a large step change of 30% in field voltage and a step change in mechanical power of up to 10 p.u. for a duration of 10 ms (page 5059).	[88]
This paper contains an extensive theoretical introduction. The authors referred to only 20 items; however, the issues under consideration were described in detail.	[91]
In the simulation studies presented in this paper, the authors used a 10% step change in mechanical torque as the cause of a transient state in a PS. It is also worth noting that, in the tested PS, in the steady state (before and after the disturbance), the terminal voltage had a large value of 1.172 p.u. (Figure 4b, page 714). The authors included only two sentences in the conclusion.	[92]
Using the example of this paper, it is worth asking the following question: why is a "broadband" PSS (which is for damping electromechanical swings in a wide frequency range) such as a PSS4B tested in a single-machine system (SMIB)? In real PSs, power swings are usually associated with the simultaneous influence of many generating units.	[93]
This paper presents research on two PSs. In the first part, the authors used a popular 4M2A system. The second part describes a large system—the North China System—consisting of 547 generating units and 8647 lines. It is a pity that the authors presented so few research results and did not show selected waveforms for the large PS.	[95]
This paper presents research on a "multi-band" system stabilizer (MBPSS) with a different structure than the PSS4B known from the literature. An MBPSS is for simultaneously damping electromechanical swings of many frequencies. It is worth paying attention to the extensive literature review, which included as many as 52 items.	[104]

Table 3. *Cont.*

Detailed Comments	Paper
In the PS analyzed by the authors, in the steady state (after introducing the disturbance) there was a power imbalance, which was evidenced by a non-zero deviation in the angular speed of the rotors of synchronous generators. It should be emphasized that, in real systems, such an imbalance is corrected by appropriate control systems.	[106]
In a 4M2A system, the influence of load characteristics on PS operation was analyzed. Two equivalent induction motors constituting dynamic loads were used as the load. It is worth emphasizing that, in a real PS, the loads are of different character. The differences in the character of loads were considered later in the paper, additionally treating loads as a source of uncertainty, which is a relatively rare but deliberate approach in the investigation of PS stability.	[107]
In the introduction, a comparative analysis of various solutions with energy storage improving the operation of PSs in transient states was made (Table 1, page 3). A solution based on distributed measurements was proposed.	[119]
As one of the issues considered in this paper, the rarely discussed problem of optimizing the location of PSS installation is presented. This problem was solved on the basis of an analysis of participation factors of rotor speed. Based on the results, it was observed (which is already known from the literature) that the appropriate allocation of a PSS improved the damping of transient waveforms in a PS.	[131]

5. PSSs in Networks with Renewable Sources

Recently, there has been a significant increase in the use of renewable electricity sources. Among them, the most popular in the context of research on power system stability are wind and photovoltaic sources, especially because wind and photovoltaic sources do not work continuously. They only produce electricity when wind and solar radiation energy is available. Consequently, PSs have to continuously compensate for the changes in active power to keep frequency constant. Additional problems may be caused by the presence of converter systems installed in renewable sources. Power electronic systems allow for the quick control of power (active and reactive) and voltage, which may adversely affect the voltage and frequency values in a PS. Moreover, the presence of wind and photovoltaic sources in PSs reduces the resultant PS inertia, which results in increased susceptibility of PSs to electromechanical swings.

From all the papers analyzed, 16 items concerning improvement in PS stability were selected for detailed discussion. The selected papers in this section are related to renewable electricity sources and, at the same time, do not belong to any of the other topics discussed in this review. On the other hand, in other sections of this review, one can find papers in which the authors also describe issues of the operation of renewable energy sources in PSs. For example, [29,32] concern classic stabilization methods used in PSs with renewable sources and are discussed in Section 2. Similarly, [52,54] contain research on artificial intelligence methods and are described in Section 3, while [91,131] are discussed in Section 4, as they deal with new regulation techniques. The research in [133], which concerns a multicriteria tuning technique of control systems in PSs with wind turbines, is also described in Section 4.

Publications on the problem of PS stabilization with installed renewable sources can be divided by the type of the analyzed sources, namely papers discussing the operation of PSs with photovoltaic installations [134–137], PSs with wind turbines [133,138–141], and PSs with water plants [142,143]. These three issues were covered by 12 papers. The next four items, i.e., [144–147], relate to the stability of hybrid networks, i.e., those in which different types of sources are installed. The first [144] concerned a hybrid wind–water system, and [147] dealt with a wind–photovoltaic system. The research in [146] discussed the phenomena in a network where wind, water, and Diesel sources were installed. In [145] (which was also considered to concern a hybrid system), the cooperation of a photovoltaic installation and a battery energy storage system was analyzed. The research in [148], which discussed transient problems in microgrids with Diesel sources installed, is also included in this section. This paper was classified as such because the issues described in it could also be related to problems in other networks, including networks with renewable sources.

As in other groups of issues, also in the case of the analysis of PSs with renewable sources, computer simulation was the main research method. Only in one case [142] did the authors supplement the simulation results with results obtained in a laboratory and in an operating hydropower plant. Simulation was also the only research method described in [143], which concerned a specific case, i.e., the improvement in dynamic properties of control systems for water sources of the Aswan dam.

For the analysis of phenomena in PSs with renewable sources, the authors of the publications chose known test systems, such as 4M2A (used, e.g., in [133,138,140]) and WSCC (used in [134,141,147]) systems. In [135,139,142], the analyses concerning the simplest case of a system, i.e., connection of the source with an infinite bus SMIB, were described. In the remaining papers, more complex PS models were used (e.g., a New England 16-machine PS was used in [137]) or the phenomena were investigated in specially designed systems (as in [145]). Standard PS models were most often supplemented with additional generating units representing renewable sources (as in the cases of the PS 4M2A systems in [133,138] or the WSCC systems in [134,141,147]). It is worth noting that, in some papers, more than one PS was used for the analysis (e.g., combination of 4M2A and New England 10-machine system, as in [133]).

Another division of the papers could be carried out by analyzing systems improving the dynamic properties of PSs.

In [134,135,137–139,141,145], uses of single-input system stabilizers such as PSS1A [50] or lead-lag stabilizers [137] to stabilize PSs were presented. The stabilizers usually had two phase compensation elements [50]. In individual cases, the following stabilizers were used for stabilization: PSS4C [147], PID [143], and a fractional-order stabilizer [146]. The remaining analyzed papers describe the developed new stabilizer structures.

As confirmation of the obtained results presented in the papers belonging to the analyzed research area, all the authors presented the waveforms of selected electrical and mechanical quantities during electromechanical transients. Unfortunately, most of the authors (eight analyzed papers) presented only one selected waveform. The waveform of the angular speed of the rotor or its increase (deviation) was presented in three papers [133,134,137], while the waveform of the instantaneous power or its increase was included in two papers [140,142]. Additionally, in two papers, the authors presented the power angle waveforms (often called the rotor angle) [141,147] and, in one case [136], the frequency waveforms of the analyzed PS. In six papers, two waveforms [135,138,148] or three waveforms [143,145,146] were shown. Only in two cases were more than three waveforms presented. As already indicated, the verification of the correct operation of power-stabilizing systems requires checking of whether both the waveforms of instantaneous power and those of voltage in PSs are within the acceptable range of changes. Such a verification was carried out in [139,143–146] by analyzing the voltage and instantaneous power waveforms. At this point, it is worth mentioning that, in two of the analyzed papers [139,144], the reactive power waveforms were presented without giving any physical interpretation of this power or a power theory that would define transient reactive power. Despite this, the reactive power waveforms in [139] were in some sense justified because they resulted from the extension (generalization) of the definition of the reactive power of an induction machine in a steady state to transient states. In this paper, the active and reactive power control systems in a wind turbine were analyzed.

Moving on to the discussion of the content of individual papers, it should be emphasized that, also in the case of the analysis of PSs with renewable sources, the power system was only an example for general considerations that was more related to the theory of regulation than to technical problems occurring in an actual system. This was the case in [133–135,137,145,147]. The consequence of this is the fact that it was difficult to move the research and, in particular, the conclusions presented in the papers to practice.

Discussion remarks concerning individual papers are summarized in Table 4. As in the previous sections, only those papers which, in the authors' opinion, stood out from the other analyzed items are discussed.

Table 4. Detailed comments on selected papers analyzed in Section 5.

Detailed Comments	Paper
This paper contains a comparison of optimization algorithms, including the collective decision optimization (CDO) algorithm, the grasshopper optimization algorithm (GOA), and the salp swarm slgorithm (SSA), used for the optimization of power system stabilizers in a network with installed photovoltaic sources.	[134]
In this paper, a one-input lead-lag stabilizer with only one phase compensation element was analyzed.	[135]
In this paper, it was proved that the regulation of renewable sources (in particular, wind farms), despite a reduction in the power generated in the source, was beneficial because the lack of such regulation had many more dangerous consequences, including the possibility of a failure in a PS and the related financial consequences.	[138]
In this paper, the problem of the uncertainty of parameters of a PS mathematical model was taken into account. The paper described the tests at a hydroelectric power plant in Brazil (a power plant with 23 generating units with apparent power of 350 MVA each). In the conclusion, the authors stated that the safe application of adaptive control techniques in real, large power plants is a challenge, as opposed to research based only on simplified computational models. The reason was that real systems have many nonlinearities and uncertainties of parameters that may not be taken into account in simplified calculation models. The authors of the publication showed improvement in the waveforms in simulation tests by applying a new regulation technique. However, the improvement in the waveforms for the real object was not significant. It should be emphasized that such a situation is natural.	[142]
The authors analyzed an actual PS associated with the hydroelectric dam and power plant in Aswan, Egypt. Unfortunately, in the paper, there was a lack of measurement verification of the analyzed case.	[143]
The authors used ready-made mathematical models of PS elements available in Matlab Toolbox. It should be emphasized that the authors analyzed symmetrical and asymmetrical short circuits (single- and two-phase to ground) without specifying in the content of the paper whether the mathematical model used allowed for modeling the phenomena occurring in asymmetrical transient states. The authors analyzed the reactive power waveforms during transient states, as well as asymmetrical ones, i.e., with distorted waveforms (Figure 7, page 5040). However, the paper did not refer to the applied power theory according to which the authors determined the reactive power waveforms in the tested system.	[144]
The paper contains investigations of a PS with photovoltaic sources and energy storage in steady and transient states. The conclusion to the paper consisted of only 62 words. They were very laconic and obvious.	[145]
The authors investigated transients in PSs with fractional-order control systems. These studies concerned, among others, the system response to a step change in the voltage reference value, including a surprisingly large change from 0 to 1 p.u. (Figure 2b, page 4).	[146]
This paper contains practical postulates, e.g., concerning an assessment of critical short-circuit times and stability margin in the study of power microgrids. In the paper, an analysis method that allowed studying the stability and influence of PSSs on microgrids was proposed.	[148]

6. Use of New Optimization Methods for Tuning PSSs

The most numerous group of papers analyzed by the authors was descriptions of research on new methods of tuning the systems stabilizing PS operation during electromechanical transients. A total of 62 papers were included in this group.

It should be emphasized that a PS (even consisting of only one synchronous generator with a drive and a control system connected to an infinite bus) is a complex control object. Consequently, a PS is an attractive example, among others, for testing methods of selecting parameters for control systems, as evidenced by the number of the analyzed papers. However, the examples described in many papers can be considered as contributions to optimization methodology rather than contributions to the development of PS stabilization methods.

The authors of the papers used many different optimization algorithms (optimization methods) to determine the desired (optimal) parameters of control systems, improving the waveforms in electromechanical transients. They included the following, among others:

- Particle swarm optimization (PSO) and its variants, including hybrid algorithms (e.g., chaotic particle swarm optimization and binary particle swarm optimization (BPSO)), which were applied 11 times in [149–159];
- The genetic algorithm (GA) and its variants (e.g., the multi-objective genetic algorithm (MOGA) and the non-dominated sorting genetic algorithm (NSGA-II)), used in seven cases [160–166];
- The farmland fertility algorithm (FFA), used in [167–169];
- The gray wolf optimization (GWO) algorithm, used in [153,170,171];
- The bat algorithm (BA), used in [172,173];
- The jaya algorithm (JA), used in [174,175].

Other algorithms, such as, e.g., the dragonfly algorithm (DA) [176] or gorilla troop optimization (GTO) [177], were used only in single cases. It is worth adding that more than one algorithm was used in some papers.

Computer simulation was the basic research method used by the authors of the papers discussed in this section. Other methods were also used only in four of the analyzed papers [178–181]. It is obvious that, in relation to control system tuning methods, computer simulation was commonly used because the most frequently used tuning methods were numerical optimization algorithms searching for the objective function extremum depending on the parameters to be set. It should be emphasized that a PS is a real system, and its elements (e.g., generating units) can be modeled in a laboratory. Therefore, measurement verification of the obtained results is desirable, although rarely used (such verification can be performed in a laboratory [7,86,142] or on a real object [142,180]). The selection of parameters for PS-stabilizing systems, including PSSs, was usually carried out with the use of commonly used test systems. In fifteen papers, at least two different systems (e.g., the simplest SMIB and the more complex 4M2O) were considered. The most commonly used test systems included the following:

- A SMIB as either the only system considered [149,152,163,164,166,168,173,175,179,182–188] or supplemented with another, more extended one [150,151,189–191];
- A WSCC as either the only PS [160,167,192–194] or supplemented in other cases [151,158,161,191];
- A 4M2O as either the only system considered [151,155,170,171,177,195–198] or supplemented with another one [133,150,176,189,190,199–203];
- A 10-machine New England as the only system [157,162,169,174,178,204,205] or supplemented with another one [133,158,161,176,199,201,202,206].

The stabilizers whose parameters were determined in the analyzed papers most often were as follows:

- Lead-lag PSSs were used in 41 works, including, among others, in [133,150–152,155,156,159–164,166–172,174,176,177,182,184,188,189,191–194,196–198,200–207];
- PID-PSSs [149,153,183];

- Robust control systems (regardless of the version) [157,186,208];
- Fractional order systems [173,185];
- PSS2As [165,175].

Other elements of PSs, e.g., PSS4B [158] stabilizers or other systems stabilizing PS operation (such as, e.g., a UPFC [178]), were tested only by the authors of single papers.

The simplest single-input PSS of the PSS1A type or its simplified version of lead-lag was the most frequently studied by the authors of the publications. The authors' experience showed that it was also often used in various PSs due to difficulties in the practical tuning of more complex stabilizers. Thus, a multitude of studies on PSS1A stabilizers could be helpful in practice. Unfortunately, most of the papers concerned a hypothetical test system (including the simplest SMIB system, e.g., in [151]) without explicit reference to practical problems occurring in real systems, which are discussed in more detail in the summary of this paper.

Taking into account the transient waveforms analyzed in the papers, it can be concluded that, in one-third of the publications (i.e., in twenty-two papers), only one waveform was presented as an effect of tuning the PS-stabilizing system. Two waveforms were presented in a similar number, i.e., in twenty papers. In four publications [178,179,191,208], no waveforms were presented. On the other hand, in 14 publications, 3 or more waveforms were shown.

Most often, the authors presented the waveforms of the angular speed or its increase (deviation), i.e., in 14 publications. In four papers, one could find the waveforms of the power angle, and in three, waveforms of the instantaneous power. The terminal voltage waveform was the only one presented in [151]. In 11 papers, the terminal voltage waveform was presented in comparison with other waveforms, e.g., instantaneous power waveforms.

Detailed remarks regarding selected (most interesting) papers discussed in this section are summarized in Table 5.

Table 5. Detailed comments on selected papers analyzed in Section 6.

Detailed Comments	Paper
In this paper, three different optimization algorithms for PSS parameters were compared. The results were compared with a "classic" PSS (as the authors called it). Unfortunately, the conclusions concerned only the analyzed algorithms and did not refer to technical problems in real systems.	[153]
In the introduction to this paper, the authors analyzed the content of as many as 48 literature items.	[152]
As a disturbance in the steady state, the authors used, among others, a step change in the driving torque.	[156,185,189]
The reference stabilizer in this research was the "classic" PSS. Unfortunately, the system with the reference stabilizer was unstable. Therefore, it was difficult to assess the solution presented in the paper.	[166]
In these papers, the authors provide a broad review of the literature.	[170,183]
The literature review in the introduction to this paper contained 36 items.	[171]
The paper is one of the few that analyzed the problem of determining the place of PSS installation. The analysis was based on the study of eigenvalues of the PS model state matrix.	[174]
In the introduction, the authors presented a review of 22 literature items. A two-input stabilizer, one input signal of which was a hard-to-measure drive torque signal, was investigated.	[175]
Only the eigenvalues of the state matrix of the investigated PS were analyzed in this paper. Despite the lack of analysis of the waveforms in the test system (without linearization), the following was stated in the conclusions: "The results indicated that the system remained stable, with high damping margin, even in different loading scenarios, demonstrating the robustness of the parameterization obtained." (page 772)	[178]

Table 5. *Cont.*

Detailed Comments	Paper
This review paper contained extensive descriptions of the analyzed problem. It deserves attention despite the fact that it does not apply directly to PSS tuning (except for one literature item regarding the coordinated design of a PSS and an SVC to maximize damping). However, the paper is an example of reliable literature research on optimization algorithms.	[181]
The authors presented a method of PSS parameter optimization based on the analysis of the position of the system state matrix eigenvalues on a complex plane. A slight improvement compared to the "classic" solution was obtained. This fact should not come as a surprise, as the actual system was analyzed in the paper. Unfortunately, the authors presented only the instantaneous power waveforms, and in this case, the generator stator voltage waveforms would also be extremely interesting. There was also a lack of research into the effectiveness of the proposed solution with regard to a larger PS.	[187]
This paper presents an interesting, practical tool for PSS tuning.	[190]
In the introduction, the authors reviewed only four literature items.	[192]
This paper deals with the interesting issue of situational awareness, i.e., the knowledge of the current and future PS state.	[198]
This paper presents an analysis of rotor angular speed after a short circuit lasting 80 ms, with the time of observation of the waveforms assumed to be as high as 100 s, during which the speed oscillated.	[199]
This paper presents an interesting method of designing a PSS for complex PSs. The method was based on the SMIB model.	[201]
Wavelet transform was used in this research on PS stability. As part of the introduction, the authors presented a description of the issues contained in 33 papers.	[203]
This paper includes a very extensive introduction with an analysis of various tuning methods. The content of the paper presents an extended description of selected algorithms. The authors presented a comparison of six different tuning methods and performed a convergence analysis.	[209]

As part of the summary of this section, it should be emphasized that, from the point of view of technical problems occurring in a real power system, the appropriate selection of the parameters of control systems (including PSSs and AVRs) is of fundamental importance. Therefore, investigations on the search for a method of their determination are very important. These investigations, however, must be related to practice, i.e., to real systems. Only in this case can their application in practice result in the expected success, i.e., improvement (stabilization) in the waveforms during electromechanical transient states.

7. Discussion and Problems

At the beginning of our summary, it is worth presenting other review papers discussing the current state of research on improvement in PS transient waveforms with the use of various types of stabilizers. The following items [210–221] were taken as examples of such papers.

A significant part of the review papers dealt with the issues of the impact of, now more and more common, renewable sources on transients and ways of reducing the adverse effects of their presence on PSs. These publications included [210–214]. In the conclusion, one can find the statement that RESs in a PS may cause greater oscillations and make the system less stable, but whether the impact of sources on a PS is positive or negative may depend on the topology of the system, as well as on the type and location of a disturbance (short circuit). Particularly noteworthy is [213], which is not a typical review paper (it contains only 28 items in the reference list); however, in its text, one can find a lot of general information about the discussed problems. It is also worth emphasizing the importance of [214], which concerned a relatively narrow problem, i.e., the work of DFIG-based sources in PSs. Despite the relatively narrow subject matter, the authors managed to analyze 125 different items of literature relating to the discussed problem.

The use of artificial intelligence methods in control systems designed to stabilize power swings in PSs was an important problem discussed in the review papers. These papers included, among others, [215] published in 2018 and discussing 187 items published after 2010. The topic of the use of artificial intelligence was also present in more general reviews, e.g., in [216].

On the other hand, the papers [170,216,217] on the use of various techniques to improve PS stability were of general nature. The authors of these publications provided an overview of a large number of literature items, from 131 in [216] to 181 in [218].

In [219], there were only 54 items in the reference list, and it was difficult to call this paper strictly a review paper concerning the damping of oscillations in PSs. Nevertheless, this paper presented comparative studies and referred to the important problem of the influence of stabilization of electromechanical swings in PSs on node voltages.

Two items [220,221], which present the problem of transients in PSs in a fragmentary way, should also be mentioned. In [220], an overview of the research to date on intelligent techniques for stabilizing power systems was presented, and for this purpose, 40 items of literature were analyzed. The authors of [221] presented a review of 56 literature items concerning various methods of damping transient waveforms in PSs.

As mentioned above, some of the research results presented in the analyzed papers were difficult to adapt to engineering practice. These problems may result from the fact that the authors usually presented general research results, to a small extent taking into account the actual technical problems, e.g., those related to situations when the data contained errors or important information was missed. As a consequence, it did not allow the full use of conclusions and sometimes forced repetition of the research in order to reliably verify the hypotheses before the practical application of the proposed solutions. This made the practical and common application of the presented solutions more difficult, despite the often very promising results presented in publications.

Without dividing the analyzed papers into individual subgroups (according to the titles of the sections), it can be stated that, in 62 out of 204 papers, only the simplest PS in the form of a generator connected to an infinite bus (SMIB model) was used for simulation studies. It is worth emphasizing that, in some cases, such a simplified mathematical PS model was sufficient, e.g., to analyze the waveforms of a generator connected to a system node with a short-circuit power much greater than the rated power of the source. However, it is difficult to explain why the mathematical models of synchronous generators analyzed in SMIB systems were sometimes so simplified. An example of such an approach can be research based on the use of a synchronous generator model without damping circuits and the selection of a PSS, which is for damping power swings, for this generator [112,151]. In such a situation, it is obvious that the omitted generator damping circuits would partially damp the power swings, and thus, the PSS would have to have different parameters or would not be needed at all. In this context, it is worth noting that the justification for such research in [151] (on page 2: "The machine was represented by its third-order linear model, where only the effects of the armature and field windings are considered.") was presented referring to a very well-known paper [222]. However, this is a paper from 1969, while the currently available techniques allow for the analysis of much more complex and, at the same time, much more accurately reflecting reality mathematical models. A different approach was used in [223], in which a SMIB system was also used for the analysis of transients. In this paper, however, the authors used a complex mathematical model of a generator and model parameters consistent with those of a real system.

It is worth noting that investigations—especially those performed in a simple system—should be verified in a real system (e.g., using measurement methods). This is difficult or often impossible due to work safety in PSs. Such validation, after confirming the assumed hypotheses, gives grounds for conducting research in a real system, or at least encourages it.

In this group of problems, it is also worth mentioning the use of models inconsistently with their scope of applicability. The most striking example of this is the study of asymmetric states using symmetric models. With regard to the discussed issues, it concerns the investigations of transient states using symmetrical models for a disturbance in the form of a short circuit, e.g., single-phase (unsymmetrical). Such action, presented, e.g., in [77,90], has no methodological justification and leads to falsification of the results obtained, which may result in a lack of reliability of these results and the conclusions drawn. It is worth emphasizing that it is also possible that the authors used the models in accordance with their intended purpose, and only the limitation of paper volume forced by external conditions (e.g., the publishing house) did not allow for a full presentation of the method used. Then, however, it can be considered as a certain oversight of the authors—not a substantive error, but a linguistic error consisting of the ambiguity of the description.

Another problem that could be noticed in the analyzed publications was the use of example (standard) parameters of mathematical models (which do not represent the real system [224]) for research, e.g., in [170]. This method is obviously correct and gives reliable results. It also has the undoubted advantage of being able to compare results for different cases. Nevertheless, it seems justified that broader research should be concluded with analyses for real parameters and not only test (example) ones. This problem is related to the problem discussed later of omitting the necessity of estimating reliable parameters of PS elements and taking into account their possible uncertainties. In this context, one more practice present in the published papers should be mentioned, namely the use of ready-made models offered by simulation programs, particularly by Matlab [153,189]. Facilitating modeling by using ready-made mathematical models of test system elements provided by software is not reprehensible in itself. Nevertheless, one sometimes receives the impression that research published in papers is a student assignment rather than serious science. In addition, mathematical models provided in the form of ready-made simulation files are not always properly described, and therefore, it is difficult to consider them as a representation of a real system because they are created as a demonstration of software capabilities.

From a methodological point of view, reasoning on the basis of the obtained results is a basic process. Properly formulated, detailed conclusions and their generalization included in the summary are the results of the research. On this basis, subsequent researchers or users (e.g., employees of companies servicing PSs) can evaluate the presented solution and continue the research or use it in practice. Excessive simplification of conclusions or reducing them only to a summary of the research significantly limits the development and implementation potential of research. In addition, conclusions that boil down to the statement that one of the tested solutions was better do not bring much to the field of science. With laconic conclusions, it is difficult to determine the advantages and disadvantages of various solutions, and thus, the potential user receives only selected data on the basis of which it is difficult to make a responsible decision (e.g., regarding the selection of the type of PSS) while minimizing the risk. An example may be the following publications: [71]—in the substantive part of the conclusion, it was stated only that (page 6) "The simulation results for three types of FFNN i.e., PNN, MLP and RBF are compared. The RBF based PSS shows its robustness over all other types of FFNN based PSSs. Hence it is concluded that an RBFFN based PSS has superior control on the negative damping effect of AVR. Such type of PSS can improve transient as well as dynamic stability of power system."; [147]—the conclusion contained only one sentence; [196]—the conclusion contained only three sentences (sixty-on words); and [197]—the conclusion consisted of only eighty-four words.

A similar effect to that laconic conclusions is achieved by presenting only selected results. Such a special case is the presentation of speed or power waveforms without showing the waveforms of voltage changes in PSs. It is then difficult to reliably and fully assess the correctness of the results obtained. An example may be the comparative analysis of two different PSSs. Their comparison with the use of angular speed deviation waveforms (e.g., using an integral criterion [174]) indicates one of them. However, it may turn out that the selected solution (better in terms of the assumed criterion) causes unacceptable voltage changes in a PS, the elimination of which is associated with such a change in the solution considered better that it becomes comparable or even worse. It can be presented graphically by marking both solutions in a two-dimensional space, as in Figure 2. For this reason, multi-criteria analyses, as described, e.g., in [133,189], are so valuable because they present solutions taking into account many, often contradictory, criteria [4,6].

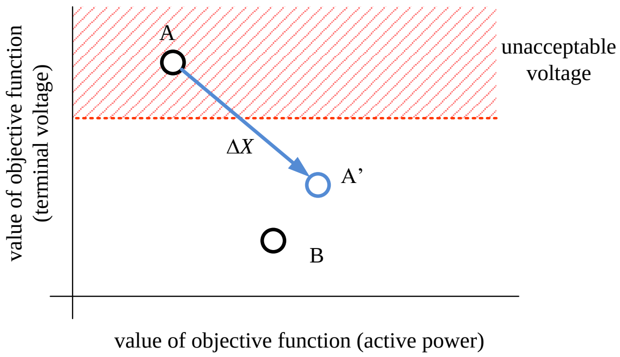
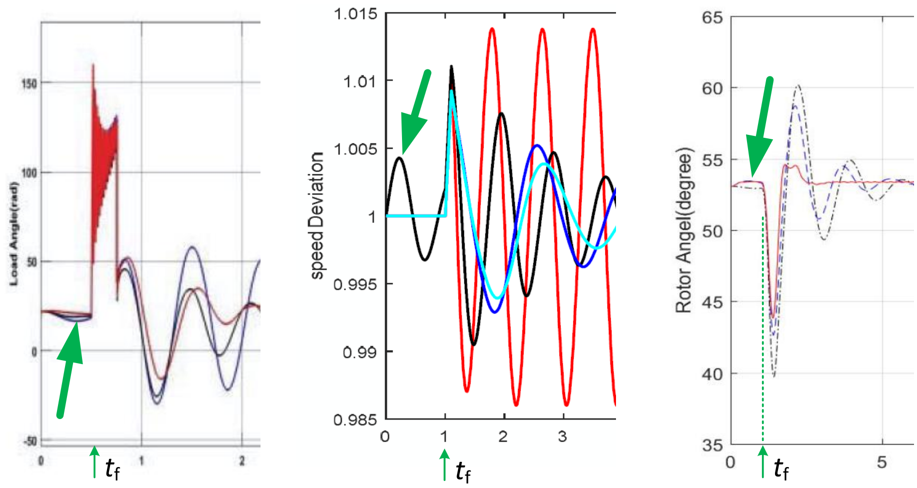


Figure 2. Graphical interpretation of an incorrect comparison of solutions based on only one criterion (A, B—original solutions; ΔX—vector of change in the properties of solution A transforming it into a new solution A').

Another important issue is the omission of technically important problems in scientific research. It is difficult to require that, in one scientific paper, all issues related to a given topic should be discussed. Nevertheless, some problems related to the discussed issue can and should be signaled. For example, when discussing simulation methods, it is worth referring to the reliability of the mathematical model (which has been mentioned in the context of simplifying the mathematical model of an analyzed PS). In particular, there are three problems: firstly, the adequacy of the model as such; secondly, the estimation of parameters; and thirdly, uncertainty imminent in PSs [4,5,76,107,142]. With regard to specific problems of PSSs often overlooked in the analyses, it is also worth mentioning the problem of the appropriate location of PSSs in PSs [131,223].

In part of the analyzed papers, unusual shapes of the obtained waveforms could be noticed that, without additional explanation, may be considered substantive errors. In this rather general context, it is worth pointing out in particular the problem of the so-called "not maintaining the initial condition". In PS simulation investigations, various disturbances are used to initiate the transient state, e.g., a short circuit in the line. The unwritten rule is that at least the first disturbance (provided that many sequential disturbances are considered, e.g., an auto-reclose relay sequence of a short circuit, fault clearing by overcurrent protection, dead time, and voltage reconnection) is introduced when the steady state occurs in the system. This approach allows for a reliable assessment of the response of control systems to a disturbance. If, however, a disturbance occurs in a transient state, the effect of the control system operation is complex and results from the disturbance and the previous transient state. Deviating from this principle (consciously or not) disturbs the reliable assessment of the presented solutions and the reliability of the comparative analysis. Waveforms in which "not maintaining the initial condition" occurred were present in many papers [20,96,126,127,129,153,155]. It should be emphasized here that such "not maintaining the initial condition" can have many causes. One of them is an incorrect power balance in the analyzed PS, which occurs in large systems where the power distribution must be determined by iterative methods. The second reason may be an incorrect algorithm for determining the initial conditions of the integrating elements in mathematical models. Both of these reasons may result from the achievement of limits in control systems that are not included in the power distribution. Another and, in the context of developing new control systems, one of the smallest problems may be instability in the system (the PS mathematical model). In all these cases, the results obtained (in a system with "not maintaining the initial condition") may be unreliable. Selected examples of "not maintaining the initial condition" are shown in Figure 3.



(**a**) (**b**) (**c**)

Figure 3. Examples of "not maintaining the initial condition": (**a**) [20] (page 1291), Figure 10; (**b**) [123] (page 3), Figure 5; (**c**) [127] (page 467), Figure 6. tf—time of the fault; arrows indicate "not maintaining the initial condition".

Taking into account the above-mentioned problems, it is worth emphasizing once again the importance of papers describing the practical use of PSSs (in a real system) [11,26,40,49,142,180,223,225] or at least the measurement verification of the obtained results [7,33,86,90]. It is also worth adding that, in practice, the methods described in papers published, among others, many years ago are still used [226–230].

8. Conclusions

The following doubts regarding the analyzed papers can be listed:

- Performing transient analyses only for the simplest systems and network systems (e.g., for the SKIB system) without verifying the results in a more complex system;
- Basing only on standard parameters of mathematical models of PS elements without referring to the problems of estimating reliable parameters of these models;
- Narrow conclusions only in the context of the research carried out without reference to technical problems occurring in real systems;
- Presentation of only a narrow part of the obtained results;
- Omitting technically important problems in scientific research, including interactions between different waveforms occurring in a real system;
- Presentation of unusual behaviors of a system that, without any additional explanation, may be considered factual errors.

In view of the above, it is to be hoped that further progress in the research on transient waveform improvement methods is based on real data and that the proposed solutions are easier to use in the industry without the need to repeat investigations (including testing the methods) so that their results can be considered reliable and applicable in a power plant.

Taking into account the extensiveness of the subject related to the stabilization of PS operation (in which there are more and more new elements connected with, among others, distributed generation and energy storage), despite the large number of publications, there is a need for further work. This applies to both research related to the use of PSSs and analysis of the available literature on this topic.

As a continuation of the work, the authors of this review plan to conduct an in-depth analysis of the available literature, particularly an analysis of the mathematical models used (adequacy and reliability of parameters), quantitative and qualitative analyses of waveforms, e.g., instantaneous power and voltage of generators (determination of regulation times and values of regulation quality factors), comparative studies of different types of stabilizers, and determination of the limitations of practical applications of solutions discussed in the literature.

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Appendix A

Table A1. Test systems used.

Power System (Test System)	Number of Papers			References
	In General	In Chapters		
SMIB (single-machine infinity bus)	79	Ch. 2	10	[14,20,21,29–34,38]
		Ch. 3	21	[51,55–58,60,61,64–73,78,80,81,83]
		Ch. 4	23	[7,80,84,86,88,89,91–93,96,98,99,102–106,118,122,125–127,129,130]
		Ch. 5	3	[135,139,142]
		Ch. 6	22	[133,150–152,156,163,164,166,168,173,175,179,182–191]
4M2A (two-area four-machine) power system	58	Ch. 2	6	[13,16,18,19,23,49]
		Ch. 3	14	[52–54,56,57,59,63,74–76,78,80–82]
		Ch. 4	16	[87,88,94,95,97,101,106,107,109,110,114–116,125,131,132]
		Ch. 5	3	[133,138,139]
		Ch. 6	19	[133,150,153,155,170,171,176,177,189,190,195–203]
New England 10 (10-machine, 39-bus power system)	26	Ch. 2	2	[10,40]
		Ch. 3	2	[82,83]
		Ch. 4	5	[85,107,108,113,116]
		Ch. 5	1	[133]
		Ch. 6	16	[133,157,158,161,162,169,174,176,178,199,201,202,204–206,209]
New England 16 (16-machine, 68-bus power system)	8	Ch. 3	1	[79]
		Ch. 4	3	[111,112,124]
		Ch. 5	1	[137]
		Ch. 6	3	[159,172,203]
WSCC (three-machine power system)	23	Ch. 2	3	[17,35,36]
		Ch. 3	2	[79,83]
		Ch. 4	6	[85,117,120,121,123,128]
		Ch. 5	3	[134,141,147]
		Ch. 6	9	[151,158,160,161,167,191–194]
NORDIC (20-machine multivoltage power system)	2	Ch. 2	2	[9,42]
IEEE 14 (5-machine power system)	5	Ch. 2	3	[10,26,28]
		Ch. 5	2	[141,147]
Other	32	Ch. 2	10	[12,13,15,24,25,27,37,40,41,49]
		Ch. 3	4	[53,58,62,77]
		Ch. 4	6	[87,90,95,104,119,124]
		Ch. 5	5	[136,143–146]
		Ch. 6	7	[154,165,200,206–209]

Table A2. Types of stabilizers used (division according to [50]).

PSS	Number of Papers In General	In Chapters		References
PSS1A (lead-lag PSS)	70	Ch. 2	19	[13–16,18–22,25,26,28,31,33,35,36,40,44,49]
		Ch. 4	9	[108,120,121,124,126,128–131]
		Ch. 6	42	[133,150–152,155,156,159–164,166–172,174,176,177,182,184,188–198,200–206]
PSS2A	8	Ch. 2	5	[21,24,29,34,41]
		Ch. 6	3	[154,165,180]
PSS2B	3	Ch. 2	2	[26,43]
		Ch. 6	1	[199]
PSS3B	5	Ch. 2	3	[27,30,37]
		Ch. 6	2	[175,207]
PSS4B/PSS4C	12	Ch. 2	5	[19,23,26,40,49]
		Ch. 4	5	[93,95,100,104,106]
		Ch. 6	2	[158,209]
PID-PSS	11	Ch. 2	1	[20]
		Ch. 3	6	[54,59–63]
		Ch. 4	1	[84]
		Ch. 6	3	[149,153,183]
Other	17	Ch. 2	3	[17,38,39]
		Ch. 4	10	[86,92,97–99,101,103,105,115,125]
		Ch. 6	4	[157,185,186,208]

Table A3. Tools used.

Tools	Number of Papers In General	In Chapters		References
Matlab	66	Ch. 2	9	[14–16,18,20,22,30,32,36]
		Ch. 3	22	[51–53,55–57,59–61,63–66,68,69,71,74–76,78–80,83]
		Ch. 4	13	[80,85,90,91,96,105,106,110,116,118,122,128,129]
		Ch. 5	5	[133,138,139,144,148]
		Ch. 6	17	[153,155–157,165,166,168,170,174,182,184,187–189,193,196,204]
DigSILENT PowerFactory	1	Ch. 2	1	[39]
ETAP	2	Ch. 2	1	[40]
		Ch. 5	1	[147]
PSCAD		Ch. 2	1	[27]
Power World Simulator	1	Ch. 2	1	[35]
PSASP7	1	Ch. 2	1	[29]
PSS-E	4	Ch. 2	2	[25,46]
		Ch. 6	2	[190,207]
Scilab	1	Ch. 2	1	[31]
NEPLAN	1	Ch. 3	1	[55]
MiPower	1	Ch. 5	1	[141]

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