energies

Review

Directions of Application of Phasor Measurement Units for Control and Monitoring of Modern Power Systems: A State-of-the-Art Review

Andrey Pazderin [1], Inga Zicmane [2,*], Mihail Senyuk [1], Pavel Gubin [1], Ilya Polyakov [1], Nikita Mukhlynin [1], Murodbek Safaraliev [1] and Firuz Kamalov [3]

1 Department of Automated Electrical Systems, Ural Federal University, 620002 Yekaterinburg, Russia; a.v.pazderin@urfu.ru (A.P.); mdseniuk@urfu.ru (M.S.); ilya.poliakov@urfu.ru (I.P.); nd.mukhlynin@urfu.ru (N.M.); murodbek_03@mail.ru (M.S.)
2 Faculty of Electrical and Environmental Engineering, Riga Technical University, 1048 Riga, Latvia
3 Department of Electrical Engineering, Canadian University Dubai, Dubai 117781, United Arab Emirates; firuz@cud.ac.ae
* Correspondence: inga.zicmane@rtu.lv

Abstract: The development of modern power systems is directly related to changes in the traditional principles of management, planning, and monitoring of electrical modes. The mass introduction of renewable energy sources and control devices based on power electronics components contributes to changing the nature of the flow of transient and quasi-established electrical modes. In this area, the problem arises of conducting a more accurate and rapid assessment of the parameters of the electrical regime using synchronized vector measurement devices. The paper presents an extensive meta-analysis of the modern applications of phasor measurement units (PMUs) for monitoring, emergency management and protection of power systems. As a result, promising research directions, the advantages and disadvantages of the existing approaches to emergency management, condition assessment, and relay protection based on PMUs are identified.

Keywords: phasor measurement unit; phasor data concentrator; relay protection; fault; digital substation; intelligent electronic device; digital communication channel; highly discrete measurements; adaptive protection; wide area protection system; continuous point-on-wave

check for updates

Citation: Pazderin, A.; Zicmane, I.; Senyuk, M.; Gubin, P.; Polyakov, I.; Mukhlynin, N.; Safaraliev, M.; Kamalov, F. Directions of Application of Phasor Measurement Units for Control and Monitoring of Modern Power Systems: A State-of-the-Art Review. *Energies* **2023**, *16*, 6203. https://doi.org/10.3390/en16176203

Academic Editor: Lorand Szabo

Received: 5 August 2023
Revised: 19 August 2023
Accepted: 23 August 2023
Published: 26 August 2023

1. Introduction

Modern power systems include a large number of elements: power plants with generators of various types, power transmission lines of various voltage classes and lengths, consumers with different load characteristics, and others. At the same time, the entire electric power system (EPS) is characterized by the unity of the mode: an accident in one component can lead to disruption in the normal operation of a significant part of the system. The reliability and survivability of the EPS depends to a high degree on the operation of the control systems. A correct and efficient management of the electric power system is possible only with the use of accurate and reliable means of measuring the parameters of the electrical mode. The EPS mode is understood as a quasi-steady state, which is determined by the values of the following parameters: power, voltage, currents, frequency, and other physical quantities characterizing the processes of the conversion, transmission, and distribution of electrical energy. Today, the EPS is a complex dynamic structure that combines power equipment and information and computing complexes that provide the control and monitoring of electrical modes [1]. Recently, due to changes in the structure of the power system in connection with the active introduction of renewable energy sources [2], the development of communication systems for transmitting telemetric information and reducing the cost of digital devices has been an active introduction and development of PMUs [3,4].

The gradual introduction of PMUs according to the works [5,6], in addition to assessing the state of the network, allows us to solve the following tasks: the verification of the dynamic models of power systems, the monitoring of intersystem power fluctuations and a search for their sources, the monitoring of the maximum permissible power flows over controlled sections and an assessment of stability reserves, the identification of emergency situations and the localization of damage, the monitoring of asymmetric modes, the verification of the parameters of replacement circuits of system elements, the development of a new generation of automatic control systems, etc. As can be seen, considerable attention is paid to the tasks of analyzing transients. The ability to control the operating parameters with the help of PMUs during such processes allows a new approach to the execution of emergency automation systems. It is often the case that in order to solve the same problems, vector measurements are introduced both in distribution networks and in microgrid networks, as noted in [7–9]. In such systems, the use of current and voltage phase measurements makes it possible, under the condition of high sampling, to organize control systems, load stability monitoring, and synchronization with the external network in a new way.

An important task for emergency management is to determine the parameters of the mathematical models of EPS based on data obtained from the PMUs [10–12]. The models of the main EPS equipment used in modern software packages for calculating electrical modes are usually characterized by many parameters that, due to the aging of the equipment and the influence of various operational factors, may change over time. In modern practice, these parameters are determined by the passport data of the equipment or experimentally during testing. The calculated model parameters obtained in this way may significantly differ from the actual ones. Updating most of them is difficult due to the lack of methods that allow determining the parameters of the equipment directly during operation. There are two main approaches to determining the parameters of the EPS equipment: active and passive experiments. An active experiment involves conducting tests during which the parameters of the electrical regime are changed forcibly. This method is associated with the risks that arise during system testing. The passive experiment consists in processing measurements obtained during unplanned disturbances in the EPS, as a result of which electromechanical transients occur. This approach has also not yet found application due to the lack of measurement processing methods that ensure high accuracy of the parameters calculated during the transition process. The data obtained with the help of PMUs can be used to quantify the parameters of the dynamic models of the elements of the EPS. Modern technologies make it possible to perform such an assessment in real time during transition processes. Determining the parameters of the dynamic equivalent of the EPS at the initial stage of the transition process allows us to obtain a quantitative assessment of the characteristics of the models of the EPS equipment corresponding to the current state of the system and the mode and nature of the disturbance, making the models adaptive. This approach does not require the use of complex models characterized by a large number of parameters. The accuracy of the model is ensured by determining its actual parameters in the current model based on real measurements and due to the fact that the model is not complicated. Also, the simplification of models leads to faster calculation, which is relevant for real-time tasks.

The purpose of this work is to systematize and analyze the directions of ultrasound applications of PMUs for the tasks of condition assessment, emergency control, and emergency protection of power systems. The meta-analysis is aimed at identifying promising areas for the use of PMUs in the conditions of the functioning of modern EPS.

The scientific novelty of the study is:

- To determine the scope of PMU application in the conditions of a modern EPS;
- Characterized by a high degree of uncertainty in the course of normal and transient processes due to a significant proportion of stochastic generation sources.

The paper has the following structure:

- Section 2 provides general information about ultrasound and the directions for the development of algorithms for estimating the parameters of the electrical mode. This

section allows you to identify the key features and directions for the development of a PMU;
- Section 3 is devoted to the consideration of the use of PMUs in the task of assessing the state of the EPS, which is the main one for monitoring and controlling normal and transient electrical modes;
- Section 4 provides an analysis of modern trends for the task of the relay protection of the EPS;
- In Section 5, the use of PMUs for the emergency management of EPS modes is considered;
- Section 6 presents the results of a review of the methods of optimal PMU placement in the EPS.

2. Development of Algorithms for Determining the Parameters of the Electric Mode Used in PMUs

A major system accident in 1965 in the USA [13] led to the active development of research aimed at increasing the observability and controllability of EPSs [14]. A separate class of studies was aimed at improving the accuracy of the procedure for assessing the state of the EPS mode by increasing the accuracy and sampling frequency of measuring instantaneous values of currents and voltages. These requirements were considered in the phasor measurement concept, which was formulated at the Virginia Institute of Technology with the financial support of the US Department of Energy, the US Electric Power Research Institute, and the US National Science Foundation.

The development of computer technology made it possible to create, in the 1970s [14], a digital remote relay using the measurement of currents and voltages of the forward, reverse, and zero sequences. One of the results of this development was a recursive algorithm for calculating the symmetric components of currents and voltages based on a discrete Fourier transform (DFT). It became obvious that the measurements of the direct sequence of currents and voltages can be used in other algorithms for the protection and monitoring of the modes of the EPS. Further research was aimed at solving the problem of the synchronization of measurements. The accurate synchronization of changes became possible with the advent of the GPS satellite system.

The Virginia Institute of Technology [14] developed a prototype of a PMU, based on which the first industrial PMU was developed with an internal GPS receiver, a 16-bit Analog-to-digital converter (ADC) for each analog input channel and several modem interfaces for remote access. A data concentrator was also developed that collected measurements from multiple amplifiers.

Existing PMU algorithms provide estimation of synchrophasors with a delay during the industrial frequency period, while traditional measurement sources can provide a delay of several seconds. Thus, PMUs allow us to describe the dynamics of the EPS more accurately, as can be seen from Figure 1.

The following main mathematical methods used for the development of PMU algorithms can be distinguished [15]:

- DFT and its modifications;
- Sinusoidal approximation algorithms;
- Hilbert transform (HT);
- Taylor series approximation;
- The Prony method.

Algorithms for estimating synchrophasors based on DFT provide a fixed accuracy for obtaining the amplitude and phase of instantaneous currents and voltages in stationary modes. The calculated DFT window should contain an integer number of periods of the fundamental frequency of the analyzed signal. The use of DFT in transient processes leads to a significant increase in the error of estimating synchrophasors. To increase the accuracy of the estimation of synchrophasors in several studies, it is proposed to increase the calculation window, which leads to an increase in the total delay of the algorithm. In works [16,17], the use of various window functions is proposed to minimize the error of estimating synchrophasors by using a DFT in transient modes of the operation of an EPS. In [18], the use of an interpolation DFT is proposed, for which the interpolation of the higher components of the frequency spectrum of the signal is used, which increases the resource capacity of the algorithm. This disadvantage can be overcome by performing calculations on a programmable logic matrix. The further development of the algorithms for estimating synchrophasors led to the creation of an improved interpolation DFT [19] and iterative interpolation DFT. Both algorithms are used for postprocessing the results of the classical DFT. The algorithm presented in [18] uses a calculated window with a width of three periods of the fundamental frequency. In the study [20], the use of DFT for the evaluation of synchrophasors in real-time mode with a sampling frequencyof 5 kHz for primary measurements is considered.

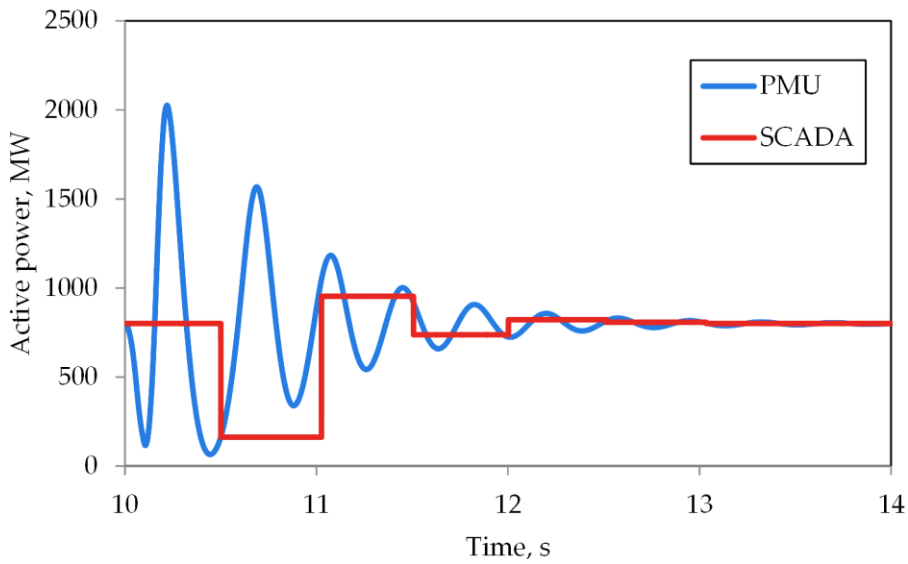

Figure 1. Comparison of active power measurements obtained with PMUs and SCADA.

The authors of the work [21] presented an algorithm for estimating synchrophasors in the time domain by using a sinusoidal approximation algorithm with three parameters [22] based on the least squares method (LSM). In [23], for the evaluation of synchrophasors, it is proposed to use a modified frequency auto-tuning algorithm in order to eliminate the effect of fluctuations in the estimated values of synchrophasors. The minimum value of the calculation window of the proposed method corresponds to one period of the industrial frequency.

To evaluate synchrophasors, the authors of the study [24] used a HT. The proposed method is characterized by a low computational load, which ensures its use in PMU class P [25]. The value of the calculation window corresponds to one period of the industrial frequency; updates of the results of the evaluation of synchrophasors are performed in increments of one period of the industrial frequency.

The study [26] presents an algorithm for estimating synchrophasors based on an approximation by a second-order Taylor polynomial. A calculated window equal to two periods of the industrial frequency was chosen experimentally. This algorithm was modified in [27] in order to increase its performance. The authors of the study [28] proposed an algorithm for evaluating synchrophasors based on the application of the Prony method. The minimum calculation window of the developed algorithm is equal to one period of the industrial frequency. Sychrophasor estimation algorithms based on the use of digital filters have found wide application in the practice of developing PMU algorithms [29]. A significant increase in the speed of ultrasounds can be achieved by reducing the size of the calculation window and step.

Thus, the current trends in the development of PMU algorithms are aimed at increasing the accuracy and reducing the delay in determining the synchrophasors of currents and voltages.

3. The Use of PMUs for the Task of State Estimation

The problem of calculating the steady-state mode of the electrical network according to the measurements was called the state estimation [30]. Because of its cyclic solution, almost all software applications for controlling the operating mode of an electric power system are performed: mode forecasting, stability analysis, the determination of control actions for emergency automation, etc. The use of synchronous vector measurements for the task of state estimation (SE) opens up the possibility to significantly improve the accuracy and speed of calculations, and therefore, in general, to improve the quality of power system management. Provided that the power system is sufficiently supplied with devices, the transition from a nonlinear formulation of the SE problem with an iterative solution algorithm to a linear formulation associated with a one-time solution of a system of linear equations (SLE) is possible. Due to the high cost, the amount of PMUs in the energy system is still limited; therefore, the integration of PMUs into the classical formulation of the SE problem based on telecommunications and their joint use is a promising area of research. In addition, there are other problems that need to be reviewed, taking into account the data received from the PMU; for example, the choice of weighting coefficients for conventional and vector measurements, the placement of measurements and the analysis of the observability of the network, and the identification of bad data. The assessment of the reliability of the PMU is of independent importance, since with the development of these measurement systems, the scope of their application in the control algorithms of normal and emergency modes is expanding. Measurement errors for these algorithms should be detected reliably and quickly. To date, many studies have been conducted on the possibility of including PMUs in SE algorithms. We consider both options for evaluating information from the PMU together with classical tele-measurements and solving the SE problem only on the basis of the PMU. The works analyze the features, efficiency, advantages, and problems that arise when introducing new types of measurements into static and dynamic SE algorithms. Some studies are devoted to the issues of the optimal arrangement of the PMU [31], including those aimed at improving the observability and minimizing the number of critical measurements [32]. In [33,34], the use of PMUs is considered for a robust SE based on the method of smallest modules. In [35], the SE of PMUs is solved on the basis of the method of control equations. In [36,37], approaches to the SE based on the use of the Kalman filter are presented, which, in addition to the current electrical mode, make it possible to determine the synchronous rotation angle of the generator rotor and the rotor rotation frequency. However, most of these approaches are very demanding in terms of equipping the PMU power system.

The active implementation of PMUs in the task of assessing the state of the EPS is possible due to the constant reduction in the cost of electronic components and the unification of devices and approaches to production. Thus, it is feasible to introduce a significant number of PMUs into the EPS.

The most common practice is the implementation of the SE based on the weighted least squares method. Many researchers considered its adaptations for the purpose of inclusion in the composition of the used measurements and PMUs. There exist several methods in the literature that were developed to account for ultrasound data in the SE based on the weighted least squares method (WLSM). These methods can also act as a basis for the development of SE algorithms based on other methods of minimizing measurement errors. Next, the main ways of including the PMU in the task of the SE based on the WLSM are considered.

3.1. Classical WLSM SE, Expanded by PMU Data

In [38,39], an approach is presented in which the PMU is directly included in the class setting and, together with the tele-measurements, participates in the WLSM SE. This expands the list of measurement types that can be used in the task.

Advantages:

- A single set of measurements is used in one procedure, which increases the accuracy of the initial data and can improve the accuracy of the assessment.

Disadvantages:

- The advantages of the accuracy of the PMU data, their synchronization, and linking to the moment of time will be partially lost due to their use in conjunction with classical telemetry;
- There is no certainty in the choice of weight coefficients;
- As the dimension of the problem increases, modern approaches to the SE aim to solve this problem, but it may persist, for example, when searching for bad data, analyzing observability, and searching for topological errors;
- Depending on the formulation of the problem, there may be some difficulties associated with taking into account currents, the angle of the base node, and measurements of voltage angles;
- The implementation of this approach will require the modification of existing SE programs, both in terms of introducing new types of measurements, and ensuring optimal design characteristics.

3.2. Linear SE WLSM Based Only on PMUs

Based on standard telemetry, the WLSM-based SE problem is solved iteratively since the equations for most measurements are nonlinear. When only complex values of currents and voltages act as measurements, and when writing the state vector in the form of voltages in a rectangular shape, a linear dependence of the estimated functions can be obtained. Thus, if the observability of the network is provided only by ultrasound, then the SE can be performed linearly by a single solution of the SE problem.

Advantages:

- Increases the speed of operation and reliability of obtaining a solution due to the exclusion of the iterative process;
- Only high precision measurements are involved;
- The matrices used in the calculations do not change as long as the repair scheme of the network and the composition of measurements are preserved;
- All measurements have a timestamp, which can be taken into account at the preprocessing stage.

Disadvantages:

- For the correct operation of the SE algorithm and the associated search for bad data, an ultrasound redundancy PMU is required, which is extremely rare in practice.

3.3. Two-Level WLSM SE Based on the PMU Framework

With a two-level SE based on the framework of the PMU [40], the measurements are divided into two groups. The first group of measurements forms a certain framework for the model under study, a single tree-like connected network. The second group makes it possible to obtain the most probable electric mode in nodes that are not observed by the PMU but have other measuring complexes. In this approach, at the first stage, a linear SE is performed on more accurate data supplied by the PMU. Next, a nonlinear SE is carried out while fixing the results of the first stage as equality-type constraints.

Advantages:

- With a certain framework, the remaining network can be divided into islands, in each of which an independent SE is performed, which significantly speeds up the calculations.

Disadvantages:

- Measurements are evaluated in groups, which reduces the efficiency of the algorithm to reduce the overall error of the measurement set;
- The PMU should be arranged in a certain way, which is difficult to achieve given the variety of the repair schemes of the network.

3.4. Two-Level WLSM SE with Post-Processing Stage

In [41,42] it is proposed to perform a two-level SE with a post-processing stage. It is postulated that most power systems are not observable only by using the PMU. To ensure the observability of the linear SE, it is possible to use the values of the state vector obtained by solving the SE on the basis of classical telemetry as pseudo-measurements represented by stress complexes. The authors propose to keep the existing SE software unchanged and use its results for new linear SE software complexes. As the results of calculations [41] showed, the proposed two-level SE with a post-processing stage leads to equivalent results to the classical SE of the extended PMU, where all information from different measuring complexes is evaluated within a single iterative procedure.

Advantages:

- The approach can have all the advantages of a linear SE with a sufficient level of observability of the PMU network and the correct choice of weighting coefficients for the measurements;
- Instead of classical measurements with reduced accuracy, a state vector obtained at the stage of solving the iterative SE problem is added as the estimated parameters, which is better than adding traditional measurements directly;
- The existing software for the SE and processes based on the results of its calculations is preserved. In this case, the transfer of these processes to a linear SE can be done after a sufficient number of calculations have been performed by the power company, guaranteeing the best result for the new algorithm in comparison with existing SE modules.

Disadvantages:

- Post-processing is performed much more often than the first stage, which means that in most calculations, it contains outdated information; moreover, it is obtained on the basis of traditional measurements, which contain a large error in comparison with the vector measurements;
- There is no certainty in the choice of weight coefficients; this problem requires careful study to properly account for heterogeneous information.

3.5. Two-Level SE WLSM Performed at the Facility and in the Dispatch Center

In [43,44], an approach to a two-level SE is proposed, where at the first stage, for each voltage class, the PMU currents are individually refined at the object level, which is performed on the basis of the first Kirchhoff law. After this procedure, based on the calculated values of the currents, the states of the switching equipment are clarified. Next, the weighted average voltage is calculated. This sequence of actions allows the calculations to be carried out without considering the resistances of network elements. At the second stage, the obtained parameters are transmitted to the dispatch center, where a full-fledged SE is performed based on a proportion of vector measurements estimated at the first stage.

Advantages:

- Parallelization of the SE process at the level of objects where the PMU is installed, due to its execution for each voltage class of each object in isolation;

- Only the results of the SE performed at the facility can be transmitted to the dispatcher center level; there is no need to transfer a complete set of data from the PMU;
- Switch states can be clarified at the object level and incorrect measurements can be rejected;
- At the object level, the resistances of the elements do not participate; the SE is performed for each voltage class based on the first Kirchhoff law as well as the calculation of the weighted average voltage.

Disadvantages:

- With the SE at the object level, the redundancy is insignificant, which worsens the quality of evaluation;
- It is required that all objects of the dispatch center model are observed by the PMU;
- At the object level, it is required that the PMU provide measurements of the currents of absolutely all connections in the object of the voltage classes under consideration;
- There are problems with finding bad data in the circuit variety; for example, if one voltage level of an object is modeled by a node with two branches, then bad data in the measurement of such an object cannot be identified since both measurements can relate to it with the same probability.

The analysis of the literature allows us to conclude that most researchers consider the SE to be promising solely on the basis of PMUs, when other types of measurements are absent. This approach significantly reduces the calculation time and makes the task linear, and providing data at some synchronized moment can allow using the results of the SE to solve problems related not only to steady-state modes but also to transients [45]. However, it is also generally recognized that it will not be possible to cover the entire energy system with vector measurements in the near future. It is widely viewed that hybrid SE algorithms, when the analysis of the power system is performed on the basis of PMUs and conventional tele-measurements, will remain useful in the years of transition from SCADA systems to measurement systems based on PMUs. As can be seen from the analysis presented, due to the differences in the quality of information provided by PMUs and classical telemetry, as well as in the frequency of its receipt, many hybrid SE algorithms focus on the separate processing of PMUs and classical telemetry. The following sections explain in detail the features of using PMUs in the SE area.

3.6. Transition to Linear SE

The use of PMUs enables switching to a linear solution of the SE problem, eliminating the iterative procedure, which will help to increase the speed of SE execution and will allow avoiding the problem of the divergence of the iterative process. On the other hand, the linear formulation of the SE problem introduces additional restrictions on the initial data necessary for its solution, and the transition to it may require the processing of existing algorithms.

Currently, many operating SE algorithms perform the solution of the problem based on the state vector, represented in polar form. When using such a formulation, the stress complexes obtained by the PMU can be seamlessly included in the task. Then, the relationship between the source data and the desired information will be linear. The problem of the transition to a linear SE in this formulation lies in the measurements of current complexes since their calculated functions have a nonlinear dependence on the state vector. The solution to the presented problem may be to change the coordinates of the state vector by moving from the polar form of its record to a rectangular one. In this case, the dependences of both the current and voltage measurements on the state vector will be linear. The transition to this form of recording will preserve the possibility of using it on a par with the vector measurements of classical telemetry. The need for its addition may arise as a result of the low level of observability of the analyzed repair scheme of the power system or at the initial stages of the implementation of the PMU. However, the introduction of power measurements will require an iterative solution to the problem since their even functions will retain a nonlinear dependence on the state vector.

One of the most important tasks in SE is the search for bad data. The problem of detecting bad data in the PMU set, as well as identifying specific unreliable parameters, is considered in [46]. Currently, the point-by-point implementation of PMUs in power systems is practiced, which leads to a large number of critical measurements in which errors cannot be minimized by SE and bad data are identified. In such conditions, even some redundant measurements can become critical when the repair scheme of the network is changed. All this prevents the search for bad data and the minimization of measurement errors and can lead to obtaining electrical modes that differ greatly from the actual ones during the SE. For the proper operation of algorithms searching for bad data and the subsequent SE, when working exclusively on data from the PMU, it is required to provide the network with an excessive number of measurements.

3.7. Features of Linear SE

The core concept of the transition to a linear SE is that when writing the state vector as voltage complexes in a rectangular shape, the values of the current and voltage complexes provided by the PMU can be calculated linearly. An additional advantage of this approach is the immutability of various matrices formed and updated under normal conditions at each iteration of the SE.

Another feature of PMUs, accounting for the SE, is the absence of fixing the angle of the base node [47], which acts as an imaginary component of the voltage when recording the state vector in a rectangular shape. Previously, with SE, information about real stress vectors was unknown, and calculations could only be based on voltage modules and some other measured parameters of the mode. In this regard, the basic voltage angle was usually assumed to be zero and did not change during the calculation. With the help of PMUs, complex voltage values can be measured and included in the SE. Like any measurement, such parameters may contain errors. For the correct operation of the SE algorithm, all measured parameters must undergo an evaluation procedure. Otherwise, for example, if a measurement with a PMU is taken as a base and there is a large error in measuring its angle, this can lead to significant errors in all of the other measurements. Thus, with a linear SE, the complex stress values of the entire system should act as elements of the state vector.

In the SE theory, the measurement equations are given as follows:

$$z = h(x) + e, \tag{1}$$

where $z = \begin{bmatrix} z_1 & z_2 & \dots & z_m \end{bmatrix}^T$—measurement vector; $x = \begin{bmatrix} x_1 & x_2 & \dots & x_n \end{bmatrix}^T$—the vector of the state of the system, which, in the considered formulation, includes the stress complexes of all nodes of the system, expressed in a rectangular shape; $h(x) = [h_1(x)\ h_2(x) \dots h_m(x)]^T$—vector of the functional dependencies of calculated measurement values on the state of the system; $h_i(x)$—a function by which the measurement value i can be obtained through the elements of the state vector x and the parameters of the mathematical model of the power system; $e = \begin{bmatrix} e_1 & e_2 & \dots & e_m \end{bmatrix}^T$—measurement error vector; m—the number of measurements; n—the number of state vector variables.

When the state vector is represented by voltages in a rectangular form, the calculated phasor measurement functions have a linear dependence:

$$z = h(x) + e = \begin{bmatrix} 1' & 0 \\ 0 & 1' \\ C_1 & C_2 \\ C_3 & C_4 \end{bmatrix} \cdot \begin{bmatrix} E_r \\ E_i \end{bmatrix} + e, \tag{2}$$

where $1'$—a matrix with zeros and ones placed on the diagonal, where vector stress measurements are available for nodes; C_1–C_4—conductivity submatrices for lines where vector current measurements are available; E_r, E_i—respectively, the vectors of the active and reactive components of the stresses, collectively forming the state vector.

The minimized objective function does not change with a linear SE based on PMUs:

$$J(x) = \sum_{i=1}^{m} W_{i,i} \cdot (z_i - h_i(x))^2 = (z - h(x))^T \cdot W \cdot (z - h(x)), \tag{3}$$

where $W = R^{-1}$—the weight matrix of the measurements and the inverse of the covariance matrix of the measurement errors.

Since the dependence of the measurement equations on the state vector is linear, their partial derivatives will also take constant values. The Jacobian of the measurements is calculated, followed by the entire system being formed, which will take a linear form, and then the SE problem is reduced to solving an SLE:

$$H^T \cdot W \cdot H \cdot x = H^T \cdot W \cdot z, \tag{4}$$

where $H = \frac{\partial h(x)}{\partial x}$—Jacobian of the measurements.

With a linear formulation of the problem, updating the matrices will be required only in two cases: when changing the network scheme or when changing the composition of the measurements. The immutability of the values of the matrix elements allows the SE to be produced by solving the SLE, preserving the results of the matrix transformations after their first execution. Moreover, in [42], it is proposed to preserve the results of the decomposition of the coefficient matrix to increase the speed of solving the problem. When using modern mathematical software libraries, this significantly increases the speed of the calculations. The matrices formed at the SE stages are also involved in other subtasks, for example, the analysis of the observability of the power system and the search for bad data. Thus, while preserving previously obtained matrices, as well as their decompositions, it is possible to use these data for many calculation cycles.

The limitation of the linear SE is the impossibility of adding classical measurements to the problem. However, as suggested in the approach of a two-level WLSM SE with a post-processing stage, the elements of the state vector obtained from the SE based on classical telemetry by using the usual iterative method can be added in the form of pseudo-measurements of high accuracy. Then the statement of the problem will retain its linear form. In this case, special attention should be paid to the weight coefficients of the measurements and the composition of the pseudo-measurements. The SE results based on classical telemetry can be used in linear SE to restore the observability of fragments of the system since such measurements will be out of sync, less accurate, and will negatively affect the result of solving the problem. If such data are added in a larger volume, then, to reduce the negative impact on the information from the PMU, their real errors should be calculated and properly taken into account in the task.

3.8. Increasing the Redundancy of Measurements of the Classical Iterative SE

The data provided by PMUs can also be useful for the classical SE task formation. For example, a new type of measurement—stress angles—can be added to the classical SE without much difficulty. Their input can increase the redundancy of measurements, but it can also become a source of new problems. In addition, various problems are observed when complex current parameters are included in the measurement vector. Next, the existing features of adding information from the PMU to the classical iterative SE based on the WLSM are considered.

The efficiency of using PMU data in SE algorithms is determined not so much by the number of measuring devices as by their location and the network design scheme. Most researchers are inclined to believe that the established PMUs will not be there long enough to perform a linear SE [48]. The installation of PMUs and modernization of measuring equipment are expensive measures. In order to be able to transmit a large amount of information provided by the PMU, it is often necessary to expand communication channels. For these reasons, the field of research related to the placement of PMUs in the network began to develop actively, aimed at minimizing the number of devices necessary for optimal monitoring of the state of the energy system.

At the initial stages of PMU input, the effect of using its data in the SE task is insignificant, or even imperceptible, when upgrading existing SE software modules. However, with an increase in the number of PMUs, it is possible to obtain SE results that are an order of magnitude more accurate than those obtained using classical measurements. According to [49], the minimum number of PMUs in the system that consistently improves SE results begins after covering one third of all nodes. In [50], it is argued that a positive effect begins to be observed when 20–25% of the nodes of the system have PMUs. In [51], the following characteristics of the influence of the number of measurements on the SE results were obtained for the 300-node system, which is graphically shown in Figure 2. It should be noted that the graph was obtained for the original scheme, where repair schemes were not considered. When considering the various factors of network repair schemes, in order to effectively reduce measurement errors, the necessary number of PMUs in the system can significantly increase.

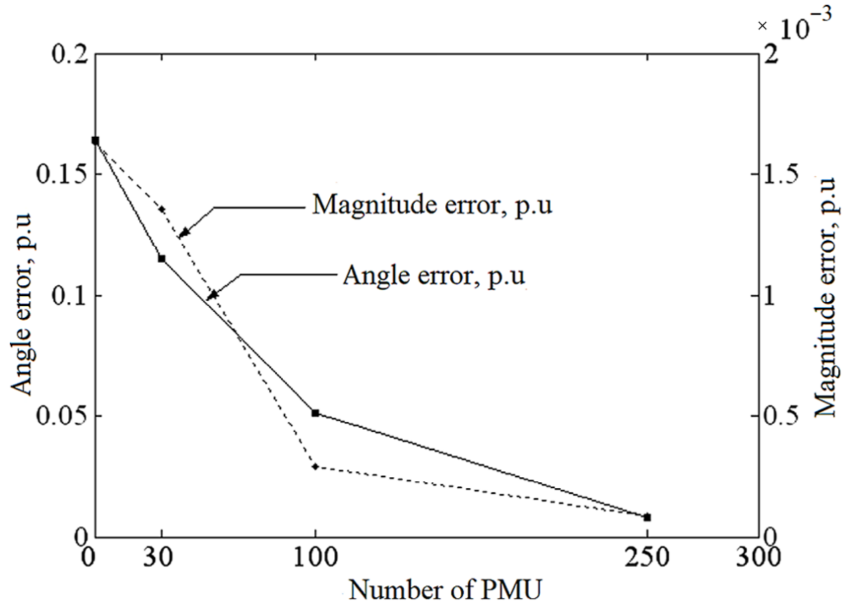

Figure 2. The effect of the number of PMUs in the 300-node power system on reducing the error in the state vector [51].

Until a sufficient level of observability of the power system is provided by the PMU, there is likely to be no tangible effect from considering the data provided by them in the SE algorithms. In such conditions, it seems promising to use hybrid SE algorithms, where the PMU will be evaluated together with classical telemetry, and the transition to a linear SE will take of a long time.

The ability to measure stress angles appeared due to the introduction of PMUs. Adding a new type of measurement to the SE algorithms does not require significant processing of the latter, but their direct use can negatively affect the overall result while keeping the algorithms unchanged.

For most of the SE algorithms currently used, the solution of the problem is built up from a conventionally selected angle by the user, usually called the basic angle and having a zero value. The choice of this approach was due to the lack of information about the real voltage vectors in the power system and the need to fix it. With the appearance of such data, the previously accepted assumption about the zero value of the reference angle becomes incorrect and prevents the correct accounting of stress angle measurements.

Initially, the researchers considered the possibility of adopting a known voltage angle, measured by the PMU, as a base node. However, this approach does not take into account and minimize its error. Instead, the error is directly added to other measurements, in which there may be no errors. Moreover, if a gross error is made in the magnitude of the measurement of the voltage angle of the base node, then the existing methods will not allow it to be directly identified. When they are used, the values of the residuals exceeding the limits can be fixed in measurements in which the errors do not exceed the permissible norms. A gross error in the magnitude of the basic angle may even cause a discrepancy in the iterative process. In [52], to detect such an error, it is proposed to compare the newly received value of the voltage angle with its previous value and respond to a large difference between them. In addition, this problem can be partially solved if the operating system uses the relative values instead of the stress angles themselves. However, most of the reviewed sources reflect the idea that the best solution is to include the stress angle of the base node in the state vector and evaluate it based on existing measurements [53].

The main influence of stress angle measurements is exerted on active capacities, which can be either represented as measurements or obtained as a result of calculating parameters after the SE through the state vector. If the power system becomes observable by means of the PMU but the set of measurements itself contains critical measurements of voltage angles, then large errors in the calculated values of active power flows may occur, exceeding the errors obtained with the SE based on classical telemetry. This is because the values of the critical measurements during the SE do not change, and if at least one of the nodes contains a critical measurement of the voltage angle, then if there is a deviation in the value of the measurement, even within the normative error of 0.1°, an error in the calculated value of the active power flow along the line can be unacceptable. First of all, the magnitude of the error will depend on the length of the line; the smaller it is, the greater the error in the value of the active power flow. In addition, the error increases with an increase in the nominal voltage class of the line. A similar situation may arise if there are significant errors in the measurement of stress angles, even for sufficiently long lines. The present problem emphasizes the need to perform an analysis of all stress angles within a single SE procedure, warning against fixing any angle as a baseline.

In addition to voltage complexes, PMUs are able to provide values of current complexes. These data are largely capable of increasing the observability of the power system. Currently, the formulation of the SE problem has become quite widespread, in which the state vector is expressed in a polar form, which leads to some difficulties in expressing complex values of currents through it. Usually, nominal stress values and zero angles are used as the initial conditions for the iterative SE. Consequently, in accordance with the calculated functions, at the first iteration of the SE, the elements of the Jacobian of the measurements associated with the currents will take zero values. This can be achieved by known methods [54]: by adding dummy shunts at the initial stages or by initializing a state vector containing nominal values of node voltage complexes with a slight noise. However, even after eliminating these disadvantages, the presence of currents in the iterative procedure significantly worsens its convergence, which negatively affects the process of solving the problem. This factor was noted in almost every analyzed source on SEs with the use of PMUs. For the analysis of complex values of currents, it is more natural to conduct an SE using a state vector represented by voltages in a rectangular shape, which is suggested by most researchers. In this case, the computational complexity of calculating the values of other measurements will not increase, and the calculation functions associated with current measurements will take a linear form.

3.9. Selection of Weighting Coefficients for PMUs

Unlike other measuring systems, a PMU provides significantly more accurate data, in particular, due to the presence of a synchronized timestamp. These features, as well as the introduction of new measuring devices in general, force us to re-consider the problems of choosing and setting measurement weights. Questions about the correctness of their definition also arise for ordinary measurements.

The weighting factors play an important role in the SE task, as they directly affect the measurement correction performed during error minimization. If we discard the reasons for the appearance of bad data, then, according to [55], the main influences on the errors of the measured values are:

- Measuring transformers;
- Measuring instruments;
- Update delays (dead zones caused by the nature of the transmission of measurements to dispatch centers).

Many studies are devoted to the problem of choosing weights for the SE problem. There is no consensus on the coefficients that should be set for the measurements. Well-known and widely used is the information about the accuracy class of measuring equipment, which is actively used in the calculation of measurement variances and later used in the SE to obtain the weights. This is a reasoned approach, although it does not take into account the existing time delays when transmitting measurements. As shown in the analysis, delays in the updating of information associated with the sporadic nature of its transmission have a great impact on the overall measurement error, and attention should be focused on them. The present analysis was carried out for classical telemetry.

The use of PMUs is desirable because of the obvious advantages, but their inclusion in existing SE algorithms based on classical telemetry creates some implementation problems. One of these problems is associated with a significant difference between the refresh rate of classical telemetry and data from the PMU. According to [56], the information from the PMU is usually updated 30 times per second, while the update of the telemetry is carried out in a time range of 2 to 6 s. Thus, the difference in the time of receipt of relevant information for classical and vector measurements should be taken into account in the SE algorithms. For example, this can be controlled by setting the appropriate weights.

There are different points of view regarding which weights should be assigned to vector dimensions in the SE problem. In [56], it is proposed to divide the weights of ordinary measurements by a certain constant. In the case under consideration, the division was performed by 100. The present approach was justified by the increased accuracy of the PMU; the choice of the constant value was not directly considered in the work. In [40], a two-level SE algorithm is proposed. At the first stage, the SE is performed exclusively according to the PMU data, and at the second stage, the information received is considered in the form of equality-type constraints in the SE algorithm, which uses classical telemetry.

In [57], a method is proposed for the automatic calculation of weighting coefficients based on the WLSM and the properties of measurement residuals, where the covariance matrix of measurement errors is iteratively calculated as:

$$R_{[i,i]}^{k+1} = \frac{R_{r[i,i]}^{k}}{S_{[i,i]}^{k}}, \tag{5}$$

where $R_{[i,i]}^{k}$, $R_{r[i,i]}^{k} S_{[i,i]}^{k}$ are the i–th diagonal elements of the matrices R^k, R_r^k, S^k obtained at iteration k, respectively. The sensitivity matrix, S, is calculated at the last iteration of the SE and is expressed as follows:

$$S = I - H_f \cdot \left(H_f^{-1} \cdot R^{-1} \cdot H_f\right)^{-1} \cdot H_f^{-1} \cdot R^{-1}, \tag{6}$$

where I is a diagonal unit matrix, H_f is the Jacobian of measurements obtained at the last iteration of the SE.

According to [57], a statistically selective covariance matrix of measurement errors can be obtained by calculating the set of retrospective measurement slices. All measurement slices must meet the following conditions:

- Be taken for an immutable network scheme,
- Have the same composition of measurements;
- Does not contain gross errors.

In [57], the operation of this method was demonstrated for classical telemetry. In [58], the described algorithm was applied to an SE based on vector measurements, where it gave a good result. During the calculation, the values of the weighting coefficients were obtained, which were approximated to those set during the formation of measurement sets during the imposition of a conditional electrical error on the conditional electrical mode. The stated limitations of the algorithm for selecting weights allow it to be used for any set of measurements. In addition to the cases considered, it can be applied to a hybrid SE when the measurement vector contains data from classical telemetry, or SE results based on it, and information from the PMU.

4. The Use of PMUs for Relay Protection

Considering the specifics of the implementation of the PMU technology, it is important to consider the scope of its application in relay protection. Modern protection complexes are autonomous systems that provide the detection and selective elimination of damage. The autonomy of their functioning is achieved by obtaining measurements and making a decision at the point of setting the terms. The encapsulation of the main parts of relay protection complexes also includes communication channels that ensure the transmission of signals over long distances, thereby achieving the required performance. In case of damage to communication channels, the main defenses are taken out of operation, and the backup ones are usually slowed down.

In the presence of extended communication channels, the integration of PMU subsystems into automatic relay protection modules should be carried out only at the level of improving their existing characteristics rather than replacing measuring protection bodies and the basic principles of their functioning with new ones. The distributed functions implemented based on PMU capabilities are more suitable for automation and slow-acting emergency automation. However, at the same time, the use of PMUs in relay protection functions within digital stations and substations becomes more justified. Especially relevant is the creation of protections on PMUs covering a variety of connections (differential) in conditions of limited bandwidth of the communication network and having almost 3–4 times less transmitted data in comparison with protections using SV streams.

With the aim of improving the protection functions, it is doubtful that the measuring and logical part based on PMUs will completely replace the traditional relay protection in terms of the new principles of its functioning, but it is expected that they will be able to significantly improve its characteristics. In case of a loss of communication with the PMU subsystem, the protections should not fail and should reliably perform their functions in accordance with the purpose.

4.1. Classification of Directions of Development of Protection Functions with PMUs

According to the requirements of the existing regulatory and technical documentation [59], particularly productive solutions should be able to implement work with instantaneous values of operating parameters in their algorithms. This opens up new possibilities for using mathematical methods for processing sampled signals that were previously unavailable for analog measuring paths. The possibilities of using PMU currents and voltages can be implemented in the following directions:

- Providing the existing protections of power system elements with new properties: expanding the properties of the traditional differential protections of lines, motors, generators, tires, and busbars; increasing the sensitivity of remote protections during swings by clarifying the protection response zone; perfecting swing blocking (SB) functions; selectively triggering overcurrent protections (OPs) by fixing the direction of the short-circuit power flow and reducing the response time due to the control of the U vectors; protecting the generators (from loss of excitation, etc.) by tracking the movement of the vector in its operation mode according to the P−Q diagram;
- Adaptive protections that adapt to the conditions of changing the mode and network scheme. Basically, these are step-by-step protections with relative selectivity, the

setpoint or characteristic of which depends on circuit-mode changes in the power system;

- Protection with a wide coverage of the protected area (due to coverage of communication channels and PMUs)—WAMPAC (Wide Area Monitoring Protection and Control).
- Centralization of the protection and automation functions in one decision-making device with action on the actuators of power system facilities through digital communication channels;
- Protections based on the analysis of trends in vector changes on the complex plane or the shape of current and voltage curves (Continuous Point-On-Wave, or CPOW technology). Mathematical apparatus: application of the DWT wavelet transform and application of AI machine learning methods.

A sufficiently high rate of measurement and transmission of PMU data, up to four times per period, allows us to apply modern methods for assessing changes in trends in current and voltage values and performing protections with a new fault detector. The existing digital signal processing algorithms make it possible to implement fast and reliable protection functions on a hardware base with low productivity. Furthermore, it is interesting to identify the moment of development of the accident before its occurrence.

It is worth mentioning that when implementing the new principles of damage detection, issues arise in ensuring the calculation of the settings of such protections and assessing the sensitivity coefficient, including issues related to the coordination of such protections and with traditional solutions in the field of protection and automation.

4.2. Solutions in the Field of Integration of PMUs into Traditional Protection Algorithms

According to the reviewed IEEE reports and the publication of the North American SynchroPhasor Initiative over five years, from 2015 to 2020, the share of research in the field of PMU application in relay protection alone increased from 4% to 15%. First of all, this research relates to the protection of lines, which accounts for 11% of publications, and the protection of station equipment, which accounts for about 4% of publications. This is due to an increase in the number of PMUs installed at facilities, the development of technologies, and digital data transmission networks. From the totality of scientific works, two relevant areas can be identified that determine the integration of PMUs into the functions of relay protection:

- The use of PMUs as part of existing, traditional protection algorithms.
- The use of algorithms based on new principles of damage detection, which are different from traditional ones.

When it comes to the relevance of using ultrasound as part of the existing protection algorithms, the obvious area of their application is protection based on the differential principle. The advantage of PMUs in such protections is not so much the response speed but the possibility of providing a wide coverage of connections and a significant expansion of the protected area due to digital communication channels [60]. In the future, it will provide protection not only for individual extended power transmission lines but also for branched sections of distribution electric networks with a voltage from 6 kV to 35 kV [61]. The latter is partly possible due to the appearance of relatively inexpensive PMU sensors (micro-PMU class *P*), the cost of which is projected to reach USD 250–300 in the near future.

The control of voltage vectors is a new concept in differential protections [62], the use of which was previously impossible due to the principle of the summation of current vectors used in differential protections. In case of damage in the protection operation zone, a difference in modulus and angle appears between the voltage vectors at the ends of the reactivated cable line, which additionally allows for the source of the damage to be fixed and the sensitivity of differential protection to be increased, as shown in Figure 3.

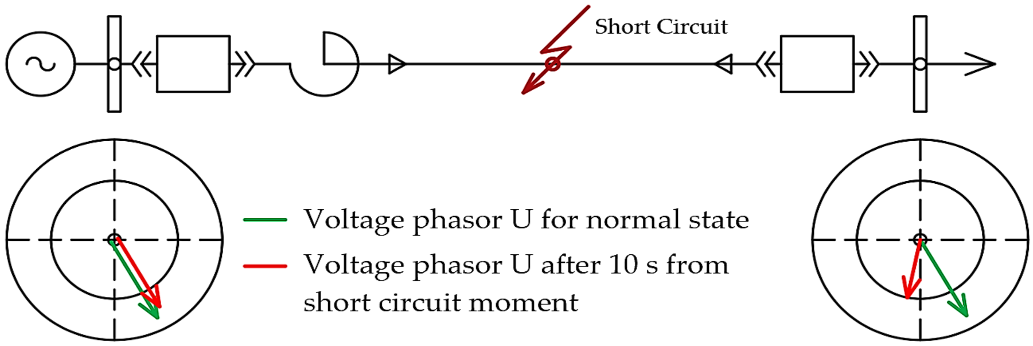

Figure 3. Change of voltage vectors in case of a short circuit on the line [62].

It becomes possible to block the magnetization current surges along the *U* angle in the case of the implementation of differential current protection in a power transformer with the control of voltage vectors.

According to sources [63–66], for redundant step protections, including current and di-station, the calculation of the parameters of the forward, reverse, and zero sequences according to the PMU vectors is carried out by applying the method of symmetric components in traditional protection algorithms. For maximum current protection, the use of PMUs obtained at the point of protection installation is relevant, first of all, when directing the power flow for fixing organs based on the analysis of the angles of currents and voltages of the phases of the same name. The initial use of PMUs in the OP of organs increases the speed of digital protection but, at the same time, worsens the detuning from higher harmonic components in the normal mode current.

In [67], the results demonstrating the effect of monitoring the bus voltage vectors of opposite substations in OPs are presented. In addition to time exposures, selectivity is ensured by identifying the damaged and undamaged elements of the electrical network for issuing permissive or blocking signals to the output protection relays, as shown in Figure 4.

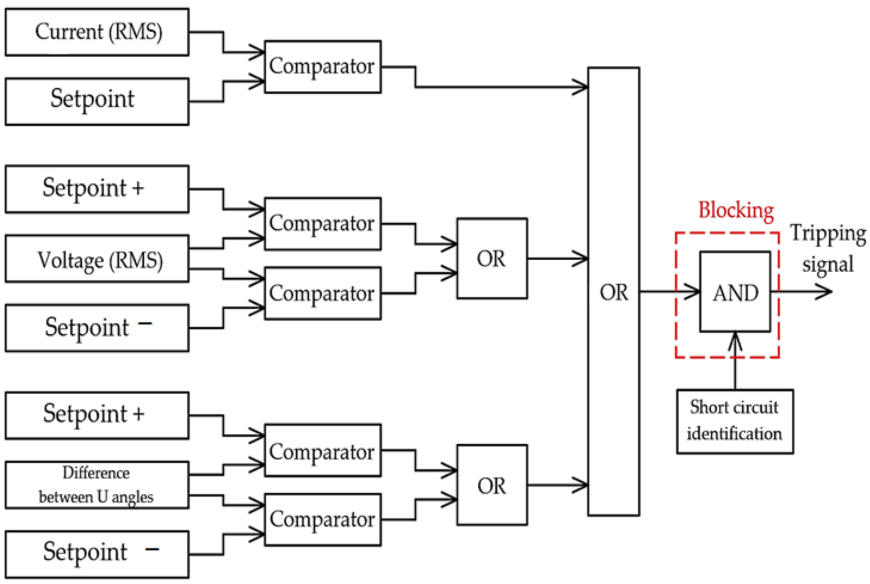

Figure 4. Block diagram of the use of voltage vectors to implement the current protection blocking function [67].

Remote protection algorithms operate on the principle of single-side measurements and are necessarily equipped with an SB. At the same time, the blocked protection may not work in case of a short circuit with a small degree of asymmetry, which occurred during swings. To solve this problem, in [68] it is proposed to use the SB algorithm based on the differential principle and to use the PMUs to calculate the differential current. Exceeding the setpoint value of the differential current permits the protection action. However, all this requires PMU sets and digital communication channels installed at opposite substations.

In general, the acceleration of the action of the first and second stages of backup protections may not make much sense in cases of a localization of short-circuit currents with a large and slowly decaying aperiodic component, delaying the transition of the current to zero for several periods.

In addition, there are technologies that improve the characteristics of existing protection algorithms based on a functional bundle of PMUs and a synchronized vector measurement concentrator. In the presence of the controlled elements of the electrical network, the existing algorithms of microprocessor protections allow for detuning from the adjustment range of flexible compensation devices, as a rule, by compromising the static form of the response characteristic, which leads to a decrease in the sensitivity coefficient of protection. To ensure accurate detuning from the adjustment range of flexible reactive power compensation devices without significantly reducing the sensitivity of the protection, a dynamic change in its settings is required. This process is not fast. The total time for the settings change is estimated at 2.2 s [69]. This should be sufficient for the operation of compensation devices that correct the parameters of the network and its operating mode, as well as in the event of circuit-mode changes caused by the work of operational personnel or the work of network automation. At the same time, if signals are lost from the system, providing additional information according to the PMU data, the protection will not be disabled and will work with the traditional static settings.

Furthermore, the development of adaptive protection algorithms is relevant for active distribution networks [70] containing renewable energy sources (RES) equipped with compensation devices.

The publications consider the improvement of the operation characteristics of remote protection directly by zones; these are the second [71] and third [72] zones, as well as the correction in response time of the stages intended for long-range redundancy in the direction of its reduction [64]. Figure 5 shows the response characteristics with the degree of longitudinal compensation of the line equal to 20% and 60%.

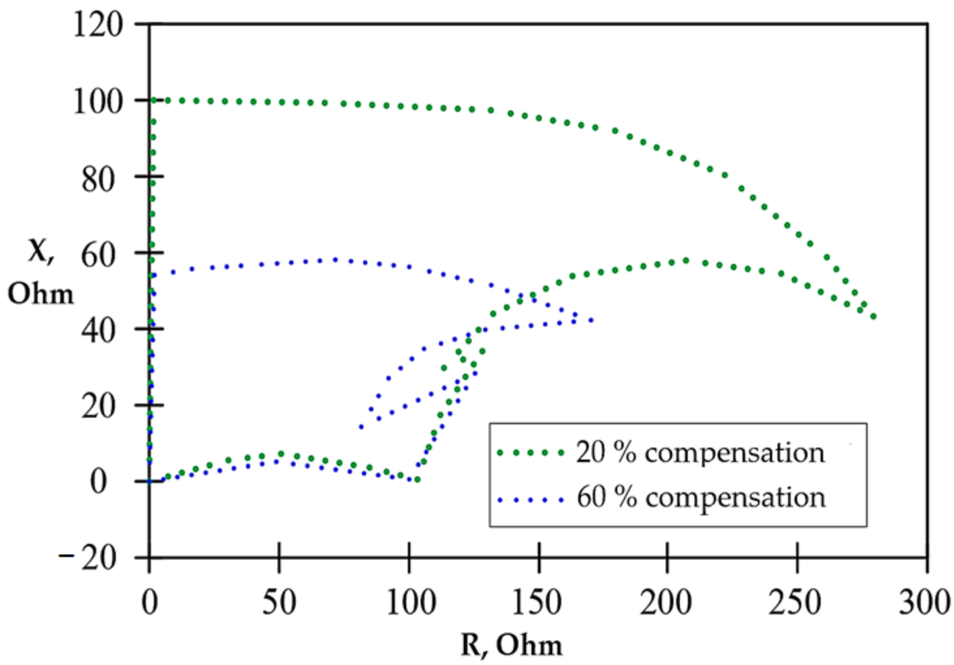

Figure 5. Characteristic of line resistance change [64].

To solve the problem of the resistance vector not falling into the zone of operation of the second stage of protection, an algorithm is proposed for assessing the degree of compensation according to PMU data, as well as the use of combined remote differential protections [73,74].

It is proposed to ensure the correct operation of the third stages of remote protection during circuit-mode changes in the network in [75] by evaluating the resistance of the direct sequence in the decision-making center (APDC), calculated and transmitted via communication channels from PMU source devices installed on different substation buses. This provides a comparison of the characteristics of the operation of the first stages and the long-range backup stages to block the latter when the first ones are triggered. PMU technologies in the backup protections of lines of various voltage classes have high applicability. Even taking into account the sufficiently long time of information transmission to the APDC and the return signal of the control action, it is possible to reduce the operating time of the stages by up to 5 times.

In addition to the protection of the lines of all voltage classes, adaptive principles can be used in the protection of generators, for example, in the protection against field loss or a loss of excitation [76], which account for about 60% of all triggers. The main problem in traditional protections based on the criterion of the limit value of the resistance corresponding to the boundary of static stability is the complexity and sometimes the impossibility of detecting damage in the ignition system during oscillations. In [76], as well as in other publications [77,78], vector measurements are used in the algorithms for determining the equivalent resistance of a system in on-line mode. Figure 6 shows the change in the shape of the characteristic when the resistance of the equivalent of the system changes.

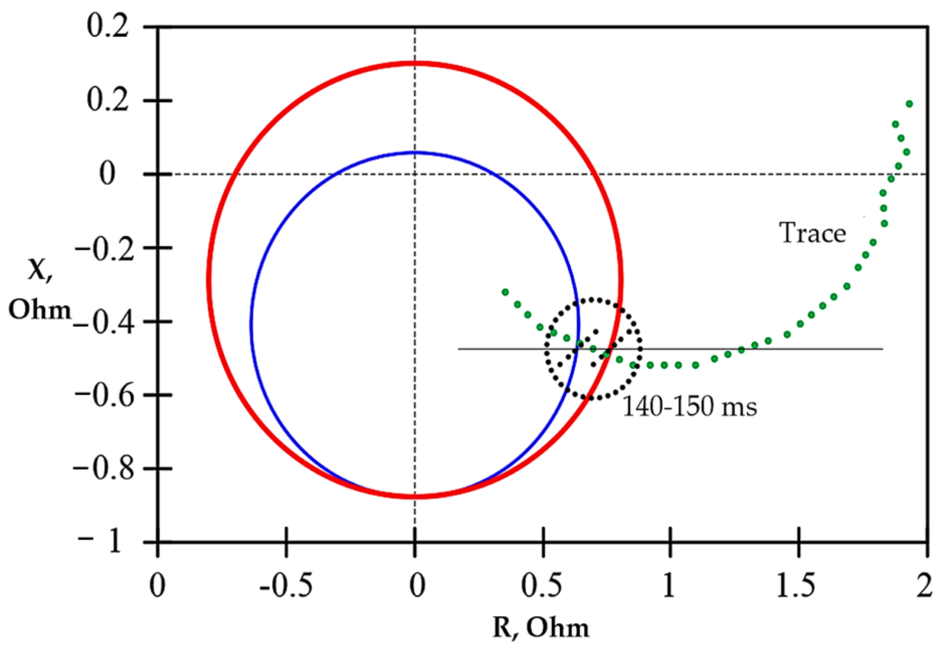

Figure 6. Estimation of damage detection time [76].

When the equivalent resistance increases, the adaptive characteristic is recalculated. If damage occurs in the excitation system of the generator, accompanied by a complete or partial loss of excitation, the reaction time of the non-adaptive protection system for entering the mode into the trigger zone of the trigger organ can reach from 140 to 150 ms. If, at the same time, the real characteristic turns out to be less, the use of protection with static charters can lead to false work caused by premature activation of protection.

Another promising direction of using PMUs to improve the protection of generators is the dynamic tracking of the movement of the generator vector along the P-Q coordinates of the diagram with control of its boundary crossing, as well as the limit on static stability for the implementation of the "soft" unloading of the generator in the case of a loss of excitation [79]. The proposed protection algorithm does not provide an instantaneous shutdown of the generator, as in traditional protections, but assumes an assessment of its capabilities for the duration of its operation without a loss of stability.

On a separate note, it is worth mentioning the automation—synchronization functions for the generation and detection of isolated work for the microgrid. Already today, there are functioning software and technical automation complexes built on the PMUs and ensuring the synchronization of the microgrid with an external public network. In electrical distribution networks, especially in the networks of large enterprises with their own generation operating in parallel with the network, automation is in demand, which ensures the determination of the occurrence of an isolated mode of operation. This is especially important when connecting a consumer to a network with power switches only on the side of the power substation of an electric grid company, without the possibility of monitoring the state of the line using the discrete signals of the switching device. This automation is included in the complex protection of distribution networks and is called RAS (Remedial Action Scheme or corrective Action Scheme), which performs the function of detecting isolated work using voltage vectors [80]. The measurement of vectors is carried out both from the microgrid side and from the receiving substation side.

The integration of all subsystems into a single centralized hardware and software platform that ensures the operation of various functions, in particular protection and automation, is a special, key direction of the development of PMUs in management tasks. The logic of this approach, described in many publications and technical reports, resembles the concept of creating the IV architecture of the digital substation (DS). It consists of using the capabilities of a common communication and computing space without the need to organize separate communication channels with related equipment and for various subsystems. However, the creation of a relay protection and automation coordination system based on PMUs is possible only with a sufficient number of PMUs.

It is noted in [81] that a system can be created for distribution networks that provides damage localization and network connectivity control based on algorithms for processing measurements and signals in a single decision-making center using the traditional measurements of the operating values of regime parameters and discrete signals without PMUs.

4.3. Solutions in the Field of New Principles of Damage Detection

Given the development of high-precision measurement devices and the increase in the computing resources of microprocessor terminals, it has become possible to develop new protection algorithms based on other principles of damage detection. Within the framework of the digital substation concept, the transition to the use of high-discrete measurements (POW—Point of Wave) with the discretization of currents and voltages in the range of 1 kHz to 10 MHz [82] makes it possible to create new starting bodies whose work is based on the analysis of changes in the shape of the curves of the operating parameters. Today, one of the most important and promising tools for working with such time series are artificial neural networks (ANNs), as well as discrete wavelet transform (DWT) mechanisms.

The ANNs, as universal approximators and classifiers, provide an analysis of the shape of curves on the basis of equipment and allow for the stable detection of damage during various circuit-mode changes in the network without correction of the setpoint. The latter, using wavelet transformations, have the ability at different levels of decomposition to analyze changes in the current and voltage curves of each phase simultaneously in the frequency and time domains, thereby providing a consistent solution to the problems of damage detection, determining its type, and determining the exact location of damage, implementing the function of determining the location of damage [83]. It is expected that the algorithms of such protections will be able to reliably complete their tasks for a quarter of the period, which is five times faster than the requirements for the basic protections. Furthermore, the creation of multiparametric protections that react to changes in the forms of several parameters at once will ensure that the initial protections in their properties approach the protections with absolute selectivity without the use of communication channels.

Due to PMUs with productive analog-to-digital converters, it has become possible to detect accidents in a time of no more than 33 ms before the moment of their development, in particular, the detection of the breakage of the conductor and the disconnection of the damaged section before the wire touches the ground. The main idea is to monitor such dynamically changing parameters using the following parameters: incremental changes in the voltage vector, angles, and voltage modules of the reverse and zero sequences.

5. The Use of PMUs for Emergency Control

The observability of the network in quasi-steady-state modes is necessary to prevent the development of emergency situations and, in general, to increase the efficiency of power system management. The peculiarity of the task of ensuring transparency in the conditions of the unity of the mode and mutual influence of electric power facilities is the large-scale nature of modern energy connections covering regions and states. In these conditions, the main difficulty is to ensure the synchronicity of measurements; the analysis of the mode must be performed on the basis of data obtained for the same moment in time. The development of global navigation systems has made it possible to introduce synchronized vector measurement devices in the electric power industry, which, due to satellite communications, determine timestamps for measurements at different points of the system with an accuracy of at least 1 microsecond and collect data on mode parameters in vector form with a given sampling.

The gradual introduction of such devices, according to the works [84–86], in addition to assessing the state of the network, allows for solutions to the following tasks: the verification of the dynamic models of power systems, the monitoring of intersystem power fluctuations and a search for their sources, the monitoring of maximum permissible power flows over controlled sections and an assessment of the stability reserves, the identification of emergency situations and the localization of damage, the monitoring of asymmetric modes, the verification of the parameters of replacement circuits of system elements, the development of a new generation automatic control systems, etc. As can be seen, considerable attention is paid to the tasks of analyzing transients. The ability to control the operating parameters with the help of PMUs during such processes allows a new approach to the execution of emergency automation systems. As noted in [87], to solve the same problems, vector measurements are often implemented both in distribution networks and in microgrid networks. In such systems, the use of current and voltage phase measurements makes it possible, under the condition of high sampling, to organize control systems, load stability monitoring, and synchronization with an external network in a new way.

5.1. Phasor Measurements and AFLS

The automatic frequency load shedding (AFLS) system is a locally distributed system: the starting and executive automation bodies are distributed over a variety of power facilities, but each device makes a decision on switching off based on local frequency measurement. The primary direction in which research is currently conducted is the optimization of the disconnected load by obtaining more information about the current operating mode of the power system.

In [88–90] there is an overview of several major accidents associated with an incomplete reduction in frequency, which entailed a serious restriction of consumption. The result of this analysis is a proposal for the use of a special automatic load disconnection, which is more consistent with additional frequent unloading. The proposed system is focused on solving the problem of stabilization after the separation of one part of the power system from another. In particular, it is proposed to use the PMU data to analyze the rate of pressure change by monitoring the value of the calculated resistance relative to the third response zone and based on this information, adjust the volume of the load being disconnected. There is a kind of acceleration of the AFLS due to the estimation of the rate of change in the regime. At the same time, the balance of each of the districts is also evaluated, as a result of which it is expected that adaptive action by the new algorithm will be achieved.

On the other hand, in [88], the PMU data is used to optimize the offload in terms of volume and localization using the solving tree model. Separately, the work considers the shutdown of units associated with air conditioning and heat removal systems. One of the tasks of the work is to minimize the shutdown of this kind of load, although according to the authors it is up to 32% for businesses and households. An approach to optimizing the disconnected load based on complete data on the energy district is being developed in [89], in which, based on the PMU, it is proposed to perform a comprehensive analysis of the operating mode of the power system and determine, in advance, the potential emergency deficits for a moment in time and calculate the optimal responses for them from the point of view of the disconnected consumers.

In addition to traditional large electrical networks, the PMU data can be used to improve the quality of the management of distributed generation installations. In [90], an approach was proposed to improve the operation of the load limiting system in networks with a large proportion of distributed generation sources, which are characterized by the use of artificial inertia algorithms. The basic idea is similar to that of the previous works: the current operating mode is analyzed from the point of view of artificial inertia systems, potential power imbalances are estimated, and then the corresponding volumes of limitation for consumers are determined, taking into account the behavior of generators. In addition, the PMU data can be used together with machine learning methods to improve the operation of consumer restriction systems when the voltage is reduced. An example of such work can be found in [91].

5.2. Phasor Measurements and AESM

The automatic elimination of asynchronous mode (AESM) is the most important part of emergency management systems. Its main task is to identify an asynchronous stroke with an electric swing center inside the protected connection. Thus, the ALAR device should be able not only to detect the presence of an asynchronous stroke but also to localize the location of the electric swing center. In domestic practice, the latter is achieved by selecting the appropriate parameters of the resistance relay used to detect asynchronous running or by transmitting the necessary information from the opposite end of the protected connection. Furthermore, an AESM installed on a generator is singled out separately, the task of which is to determine the presence of an asynchronous stroke inside the block, which is equivalent to the loss of synchronism by this generator.

Since it is impossible to predict in advance in which section the asynchronous stroke will occur, the use of PMUs for AESM is promising. The basic approach is to solve the classification problem in terms of the presence/absence of asynchronous running inside the network section under study and by localizing the electric center of swing (ECS), for which both computational methods and machine learning methods can be used.

Thus, in [92,93], a new approach to the analytical determination of ECS is proposed based on the transformation of the topological stress diagram, in which the stress of the angles remain stationary, and the zero point corresponding to the ECS moves in the presence of an asynchronous stroke. In addition, a hierarchical system for determining the presence of asynchronous running and the localization of the ECS is described, followed by determining the optimal section for separation depending on the power balance. The search for the optimum is performed using the search tree.

In [94,95], the AESM function is considered from the point of view of the classical classification problem. In the first case, a decision tree model is used to determine the presence of an asynchronous move. In the second case, the AESM functions are included in the composition of the multi-criteria protection of the line presented in the work, based on the PMU data at its ends.

In [96], on the contrary, PMU data are used to refine resistance measurements, which leads to an increase in the quality of automation. In [97,98], approaches to improving the AESM installed on the generator are proposed. In the first case, the PMU data are used to improve the quality of work relative to the traditional approach to determining asynchronous running, reminiscent of ECS algorithms. In the second case, a naive Bayesian classifier trained on synthesized data is used to determine the asynchronous stroke.

The disadvantages of using AESM based on PMU devices installed only at the ends of the protected area are also noted. In particular, the operation of automation will become impossible if the communication between the devices is disrupted or if one of the measuring complexes fails. To take advantage of such an AESM scheme, it is proposed to increase the reliability of automation by adding a backup stage in the form of a traditional AESM operating according to local measurements. At the same time, the presence of vector measurements will make it possible to update the settings of the second stage depending on the circuit and the network mode.

5.3. Phasor Measurements in the Problem of Identification and Advanced Network Division

The identification of divisions and the adaptive types of automation of an advanced network division are two directions of development for emergency management systems, which received an impetus for development from the spread of PMUs in system-forming and distribution networks. Division identification is a task solved mainly for microgrid networks, in which, depending on the mode (isolated or parallel operation with an external network), the distributed generation control mode should change, or the internal consumption should be gradually limited. In the case when the isolated operation of the distributed generation is not possible, when separation from the main network is detected, the generators are turned off to avoid asynchronous running. In turn, for a system of high and ultrahigh voltage classes, the analysis of data from distributed PMUs allows, at the pace of the transition process, for the selection of areas that should be separated from the main network to keep the generating equipment of power plants in operation.

Although it is a promising direction, there are few publications devoted to the use of PMUs for the implementation of these types of management. This is largely because the use of vector measurements is not necessary for microgrids; there are few connections with the system, and their operating mode is controlled in simpler ways. Nevertheless, as part of the review, attention should be paid to several interesting works.

In the study [99], an algorithm for adaptive advanced network division based on PMU data is proposed. To assess the need for network division, an indicator of the severity of the frequency mode is used—$FbSI$. In fact, this value characterizes the acceleration of the rotors of the generators of the system relative to the center of inertia of the network, but only for the period from the occurrence to the elimination of the disturbance (for example, for the time before the elimination of the short circuit). Based on the prepared $FbSI$ database for previous modes, the threshold value of the $FbSI_{sev}$ indicator is selected based on the clustering results, at which the network must be divided to keep the generating equipment in operation. Figure 7 shows the trajectories of $FbSI$ changes over time and the grouping of scenarios according to the severity of the disturbance in the system.

The choice of network division schemes is made in two ways: using a dynamic model of the power system and an analysis of pre-emergency mode parameters on the one hand and using clustering measurements of the voltage angles of nodes to identify mutually accelerating groups of generators on the other. From analyzing the proposed schemes, it is found that the first preserves the stability of the network equipment, and the other has the potential for the smallest power imbalance. The solution was tested on the WSCC test model and on the current dynamic model of the Turkish power system. In all cases, the proposed network division option allowed the system equipment to be kept in operation. Depending on the clustering method of the generator measurements, the calculation time ranged from 0.001 to 0.068 s. This speed was achieved, among other things, due to parallel computing.

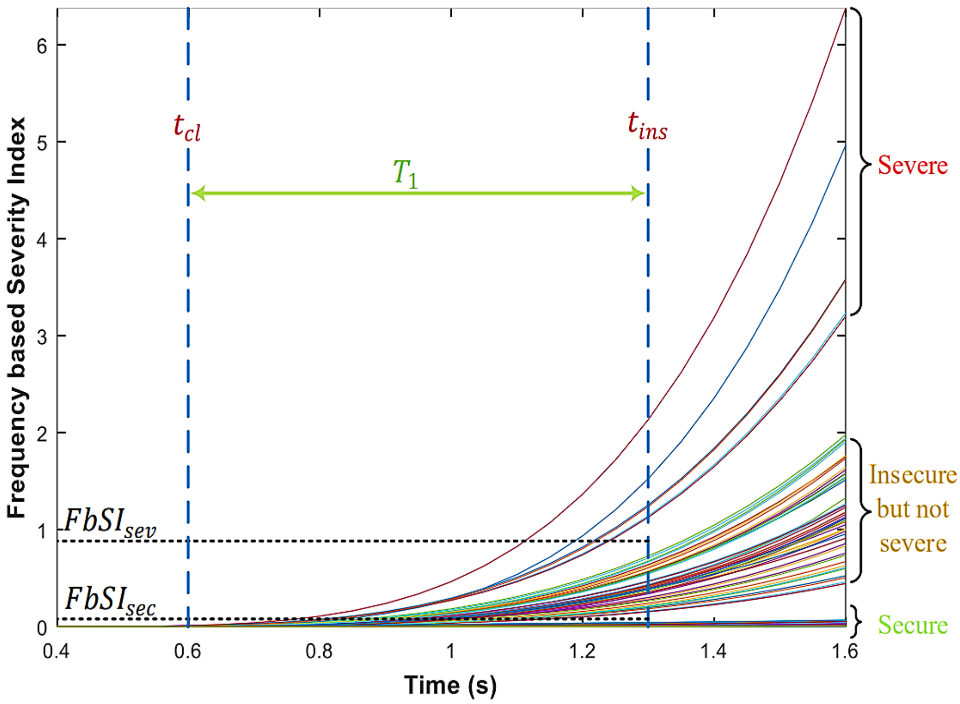

Figure 7. $FbSI$ change trajectories for various scenarios in the test power system and the threshold value of the indicator for network division [99].

The authors of [100] hypothesize that the separation of the network can be fixed by changing the angle between the voltage vectors of the forward and reverse sequence. Thus, it is proposed to install the device only at one node—at a station of a detachable network, the generators of which will be loaded or unloaded according to the results of the evaluation of the isolated part of the network. The main advantage of such a solution is the absence of communication channels and the exclusion of the possibility of external malicious actions disrupting the system. The time required to identify the separation from the external network does not exceed 10 ms. At the same time, to detach from short circuits, load changes, and the mode of operation of the reactive power compensation, the range of angles between the vectors that make up the voltage in which the angle is located when the network is separated is determined. The system will give a signal to change the mode of operation of the generators only if the measured angle falls within the found range.

In [101], a branch of the microgrid network is identified, for which the generators' isolated work is not provided. It is assumed that when detecting a mode in which the system is separated from the external network, its generators should be turned off to avoid the development of an emergency situation and an occurrence of asynchronous running. To do this, it is proposed to use the bootstrap aggregation algorithm, which is trained using the measurements obtained from the PMUs installed on connections to the external network. The training sample is selected in such a way that all the scenarios included in it correspond to the six operating conditions of the isolated network operation monitoring device in accordance with the IEEE 1547–2003 standard: measurements of reactive generation power, short circuits near the network dividing point, load surges, load drops, changes in solar generation power, and poor measurement quality. According to the results of testing in 100 test scenarios, the authors claim 100% accuracy of triggering at the zero zone of insensitivity of the algorithm, which, however, raises doubts. Nevertheless, the general approach to solving the problem is promising and can be adapted to the function of changing the operating mode of generating devices rather than turning them off.

The study [102] is devoted to the development of an algorithm for the anti-accident automation of advanced network divisions. The central part of the algorithm consists of two neural networks, each of which solves its own problem. The first evaluates the dynamic stability of the system after a perturbation by the rate of change in the relative angles of each of the generators of the system for two consecutive measurements over five cycles. The second, in turn, predicts the trajectories of changing the angles of the generators of the system for 15–20 cycles. This network compares trajectories with a library of models prepared in advance, solves the classification problem, and indicates whether one or another generator will come out of the synchronism in a set period of time. In order to determine which switches need to be made, an algorithm for finding the optimal network division is used. According to this approach, first, nodes are grouped by their distance from the generators that can break out of synchronism; second, the connections between the nodes that need to be disconnected are determined in order to minimize the imbalance and the amount of interrupted power flows. The algorithm was tested on the New England-39 model. The accuracy of the proposed model was about 98%. In [103], it is proposed to use data from the PMUs to identify outages of the system elements and change its topography.

In microgrid networks, their small scale is a limiting factor for the development of automation systems for the identification of network division based on PMUs. In most of the works presented in the review, the proposed algorithm of emergency automation is implemented for a single switch connecting a small system with an external network. The justification for the use of PMUs in this case is not the synchronization of measurements but the possibility of using additional signals in parallel operation control algorithms, such as, voltage phases. At the same time, there is also a reverse trend towards the development of systems for identifying isolated work strictly without PMUs in order to ensure cybersecurity and simplify the principles of automation.

The use of PMUs in advanced network divisions may be more promising in the case of large systems and the implementation of adaptive dividing automation. In this case, as shown above, it becomes expedient to use machine learning algorithms to reduce the decision-making time as the conditions of the development of an emergency scenario. Nevertheless, the specifics of this type of automation should be noted. Thus, the implementation of an adaptive algorithm for dividing the system is probably necessary in cases where it is difficult to identify potentially balanced areas earlier. This is possible, for example, with a significant share of renewable energy sources (RES) in the composition of generators. In addition, dividing automation operates in situations where other measures to contain the development of an accident have been exhausted. Under these conditions, it is important to test the potential algorithm on a real scenario, which was not carried out in the considered cases.

Thus, the expediency of identifying the network division using PMUs is controversial. For microgrid networks, the scale of the task being solved is often too small. For integrated power systems, additional research is required aimed at verifying the algorithms of emergency control automation (ECA) in real conditions, taking into account the poor quality of data as well as assessing the consequences of the erroneous operation of such systems.

5.4. Phasor Measurements in the Problem of Identification and Damping of Electromechanical Oscillations

The detection and damping of electromechanical oscillations is one of the most suitable areas of PMU application, since the data collected allows monitoring the dynamics in the area of the power system as a whole, observing and detecting various oscillatory modes related to both intrinsic and intersystem oscillations.

In [104], the authors propose a method for solving the problem of determining the source of undamped low-frequency oscillations. A similar task is solved by the PMU system, but with respect to synchronous generators only. The source of oscillations is determined using a trained classifier using the k nearest neighbors method. The training sample was formed based on modeling various processes in test systems by artificially provoking vibrations by different devices. For the operation of the system, it is assumed that each generator is equipped with a PMU data transmission device, an observation window of 5 s was considered at a sampling frequency of 25 Hz. The algorithm achieved accuracy of determining the source of oscillations above 96% for the case of an IEEE-179 node circuit containing 29 generators. In situations of incorrect identification of the source, the detected unit was still electrically close to the real source, which somehow reduces the search area.

A natural progression of research in this direction is the development of methods for damping electromechanical vibrations based on PMU data. In [105], an approach to adaptive selection of PSS parameters based on machine learning methods and PMU data is proposed. In particular, it is proposed to use an ordinary random forest model to identify two main cognitive modes. The parameters of the regulator are then selected in such a way as to dampen these vibrational modes most effectively. The authors justify the choice of a random forest model by the fact that traditional methods, such as Prony or discrete Fourier transform, often require a large observation window, which increases the reaction time, in addition, they provide fairly good accuracy by evaluating high-order models, which can lead to undesirable artifacts in the data. Evaluation of the operation of the proposed algorithm on a standard four-machine Kundur model showed good results in terms of damping. Within the framework of this approach, the PMU data should ensure the observability of the network and are used to train the model of identification of oscillatory modes by teaching with a teacher.

Clearly, the PMU data are a tool not only for detecting sources of low-frequency oscillations, but also for damping them. Thus, in [106], an approach for vibration damping is proposed based on the use of an agent trained by reinforcement learning methods. At the same time, it is proposed to use a small signal in amplitude to study the dynamics of the power system, and the automatic excitation regulator (AER) of the generator is based on the identified dynamics.

As shown in [107], along with excitation regulators, static reactive power compensators can also be used to dampen vibrations. In the paper, a neural network model based on fuzzy logic is considered as a control tool. And in [108], it is proposed to use not only compensation means, but also charging stations for electric vehicles to dampen vibrations and control the operating mode of the distribution network: again, as additional sources of reactive power. The paper also discusses various scenarios for using the proposed algorithm, including different scenarios of equipping the network with PMU devices.

In [109], on the contrary, it is shown that simple synchronization of AER devices allows to improve the quality of damping of electromechanical vibrations simply because control actions and measurements enter the devices synchronously at the same time, that is, AER devices react to a system located in the same state standing. The paper shows that in some cases the effect of such synchronization can be significant and maintain the stable operation of the power system.

In [110], neural networks are used to select the AER coefficients. Finally, the study [111] proposed three methods for evaluating the participation of a synchronous generator in damping low-frequency oscillations. All three methods, based on different data sets from the PMU, assume an estimate of the specific synchronizing power of the generator—the partial derivative of the power of a synchronous machine by its load angle. In the first case, this value is estimated directly for each moment of time. According to the second method, the load angle for the generator is calculated according to the design parameters and factory characteristics of the generator. In the latter case, with the least variety of data from the PMU, expressions for the second method are used, but the parameters are considered constant and independent of the load and the excitation current. Analysis of the trajectory of the specific synchronizing power allows you to evaluate the quality of the regulators. Nevertheless, the authors note that the error introduced into the calculation result by the accepted assumptions can be estimated only by the results of field experiments.

5.5. Phasor Measurements in the Problem of Identification and Damping of Electromechanical Oscillations

One of the consequences of the use of PMUs for damping electromechanical vibrations is the creation of local and centralized control systems for the operation of the power system and the prevention of instability. In [112], a method of voltage regulation in the network using flexible alternating current transmission system (FACTS) devices is proposed. The control is based on the identification of the dynamic model of the power system according to the PMU data and the calculation of the necessary control actions to maintain the voltage. As a result, it is possible to deal much more effectively with voltage drawdown in the case of various disturbances. Furthermore, in [113], reinforcement learning methods are used to control the power system mode.

Separately, it is necessary to highlight the works devoted to determining the volume of generation unloading based on PMUs to prevent the violation of dynamic stability [114–116] at the pace of the transition process. In other words, it is proposed to use the PMU data to build automation, which determines the necessary change in the generation power in the node in the period from the moment of occurrence of the emergency mode to the occurrence of the asynchronous mode. The authors in [117] propose a method for the rapid evaluation of the parameters of the electric mode for subsequent use of the obtained values when solving the problem of unloading generator turbines in order to prevent stability violations. This approach is based on the approximation of the signal by the first terms of the Fourier series on sliding windows using a multiparametric model. Using the example of a single-machine model of the EPS, it is shown that the proposed technique allows for the estimation of the parameters of a dynamic process with delays from 3 to 5 ms and an error in parameter estimation not exceeding 1%. The results are used in the works [114–116], respectively, for single-bus and multi-machine systems for the implementation of the emergency control of synchronous generator modes. In particular, the additional kinetic energy of the generator rotor is estimated based on the results of the evaluation of the parameters of the mode, the identification of the disturbance and the emergency mode, its operating mode is predicted, and the need for emergency actions is determined: either pulsed turbine loading or, in the case of an inevitable loss of synchronism, the generator is turned off.

5.6. Phasor Measurements in the Problem of Identification and Classification of Emergency Events

In the task of identifying and classifying events, the source is a set of measurements from the PMU installed at different points of the network, according to which it is necessary to determine the occurrence of an emergency situation in the system, the place of the accident and its source, and the type of disturbance. These allow us to take timely measures to prevent the development of local incidents into systemic accidents. At the same time, machine learning algorithms, which play a key role in this area of emergency management, allow the task to be solved at a real-time pace. The rapid preliminary identification and localization of events are necessary for the implementation of any kind of adaptive automation. Unlike other anti-emergency management tasks solved with the help of PMUs, the methods developed for classifying events are tested on real measurements.

In the first study [118], a model is developed for recognizing and classifying events that can be trained on real data and checks the accuracy of its operation depending on the approach used to mark up the data of the training sample, namely fast, medium, and full markup. The measurements of voltages, currents, and frequencies at the points of the western energy union of the USA for 2016 and 2017 with a frequency of 30 and 60 measurements per second were analyzed. Events are divided into three categories: normal mode, short circuit on the line, and system frequency deviation. These three groups, as can be seen, cover a large number of types of events. The authors adhere to such a non-strict classification since one of the goals is to check the possibility of detecting and separating local and system emergency events based on a limited set of data from the PMUs. The paper discusses various approaches to data markup and compares the following classification tools: decision tree (DT), multinomial logistic regression (MLR), neural network with direct signal propagation (FFNN), single-channel convolutional neural networks (SC-CNN), and multi-channel convolutional neural networks (MC-CNN). The authors attribute all solutions except the last two to the traditional ones. The results showed that the highest accuracy of the assessment—91.1%—is achieved when using a multichannel neural network with parallel filtering in the case of a complete analysis of the training output at the stage of marking measurements from the PMUs. As the quality of training decreases, the accuracies of 88.4 and 83.3% for the fast and medium markups decrease, respectively. It is important to note that of the traditional methods, the support vector method is the best, the accuracies of the results of which are acceptable and are estimated at 83.7, 79.8 and 77.0% respectively. At the same time, this solution is much easier to implement.

In the work [119], by the same team of authors as [118], LocIT training was implemented to identify emergency events in conditions when the training sample is small and the PMUs are distributed throughout the system. To build the model, we also used real data for 2016 and 2017 for the western part of the US power grid. To test the effectiveness of the implementation of the proposed method, its effectiveness was also compared with other solutions, including algorithms that do not require training, such as the methods of k-nearest neighbors (kNNs) and nearest isolated groups (iNNEs). The work, in addition to demonstrating the high accuracy of event identification using transferable learning (about 93%), describes how the size of the window of observation of the transition process and the size of the training sample affect the results of the training and identification. Figure 8 shows an error (AUROC metric) in identifying events depending on the width of the window and the proportion of the training sample in the total data array. Here, in addition to the results for LocIT, the values for the kNNs, the kNN method with reinforcement (SKNNO), and the multilayer perceptron (MLP) are shown. The results of the study lead us to conclude that, with a limited number of training samples, it is better to limit the width of the observation window. The effectiveness of the transference equipment in this case is also obvious.

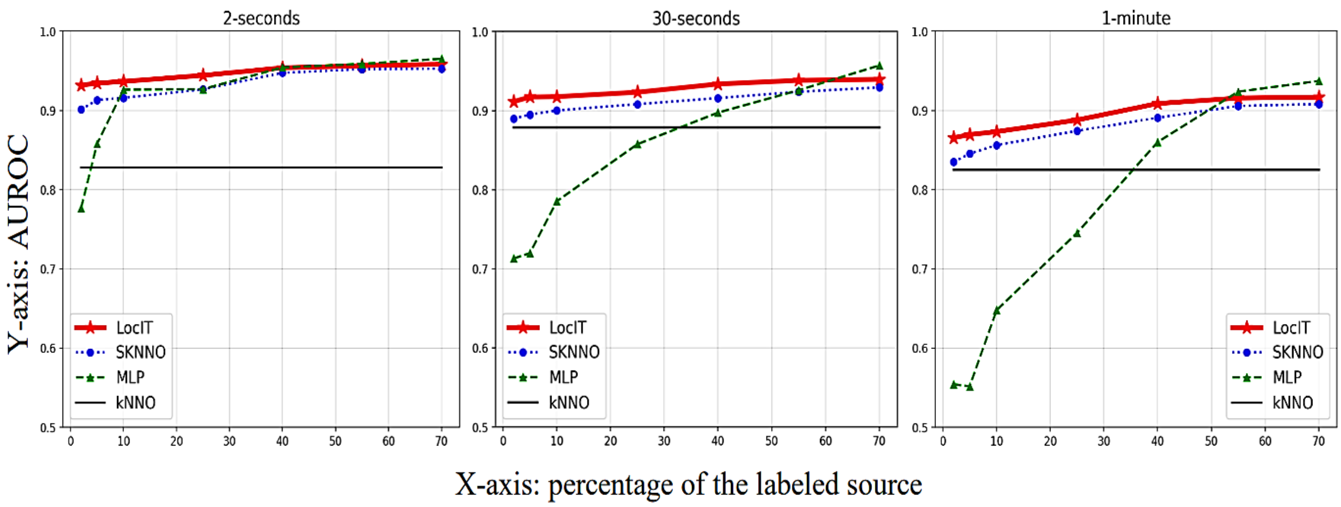

Figure 8. AUROC event identification error depending on the proportion of marked-up data in the total sample at the window width: 2 s, 30 s, and 1 min [119].

The paper [120] proposes several methods for identifying and classifying events in the distribution network according to PMU data. In particular, the support vector machine (SVM) learning algorithm was applied, which was further compared with the kNN and DT methods. To mark up the data, real information from power supply organizations and their expert assessments of events were used; the classifier was trained on data for 15 days from two devices at the ends of the feeder of the Riverside distribution network. Measurements of current, voltage, and active and reactive power flows were used for the training. Considerable attention in the study is paid to the use of a variable sliding window to better capture events in the network. The technique assumes the localization of the area of the source of disturbance from the supply side, from the consumer side, and between the PMU installation points. At the same time, ths events are typed only for the third case, and the following scenarios are distinguished: sudden changes in consumption, switching of a battery of static capacitors (BSC), and other events, which include, for example, short circuits. Calculations show that the accuracy of the detection, localization, and classification of events for all algorithms is high—at the level of 95%, but for the SVM method, it reaches 100%.

The study [121] proposes the implementation of a deep neural network for the identification and classification of events in real time. The authors propose a methodology for processing data to improve the effectiveness of training convolutional neural networks and also describe a regularization algorithm for implementing deep learning. The trained network detects events and divides them into the following categories: absence of disturbances, switching of lines, switching of generators, and oscillation of generators. In addition to the complex and effective machine learning model, the work is of interest for its experimental work, in which the model is tested on two-year measurements of frequencies, capacities, currents, and voltages from 187 PMUs installed in the network of the eastern energy union of the USA. Taking into account the low quality of a number of the measurements, the proposed method gives an identification accuracy of at least 93%. At the same time, although neural network training takes more than three hours, it takes only 0.085 s to perform the classification in real time.

In the study [122], a method is proposed for classifying events associated with frequency deviations using PMU data. The authors consider this problem from the perspective of a distribution network operator, which needs to quickly establish the source of disturbance to make decisions in the conditions of the emergency events. In particular, the question is whether the frequency change is caused by an external disturbance in the high-voltage network, or its cause is a change in the operating mode of electric receivers and feeder sources of the controlled distribution network. In the first case, as the authors note, the disturbance is of a large-scale nature and is reflected immediately on all measurements of the PMU, which serves as a criterion for separating events. To identify the source, the study uses the Granger causality and the Hodrick–Prescott filter. The verification of the proposed solution is carried out on the basis of data provided by the Berkeley National Laboratory and the Riverside Power Supply Company on measurements from three feeders in the period from July to September 2015. For data processing, the method of sparse coding with training is used, and the k-means method is used for clustering events.

A significant number of papers also consider the possibility of identifying and classifying events but do not test the performance of the proposed methods on real data. The results in this case depend on the method of generating artificial measurements and taking into account the poor quality of data from the actual PMU, since standard power systems serve as a test model.

The study [123] is devoted to solving the problem of classifying short circuits in the distribution network. The work has distinguished several types of classification. In particular, there are 34 types of events, including 11 types of short circuits, and breaks from the supply side and from the load side. K-NN and SVM machine learning algorithms are used as event classifiers. Their training is carried out on the following measurements of the PMU before, after, and during the disturbance: currents and their phases and the parameters of the forward, reverse, and zero sequences. To form a training sample, more than 26 thousand different perturbations were modeled in the IEEE-123 test model at a voltage class of 4 kV. At the same time, only two cases were considered—the installation of one or five PMU devices, and disturbances were modeled only at eight points of the network. In contrast to other studies, the use of trained algorithms on average did not give a high classification accuracy at the level of 50%, although for some types of short–circuits this characteristic reaches 90%. The best results were obtained by small neural networks and SVMs.

In [124], a complex structural model of a deep learning neural network is proposed, the task of which is to search for and localize disturbances in the electrical network with their subsequent classification. To identify events or, as they are called in the work, anomalies, the authors propose to use an auto-encoder. A continuous stream of PMUs are used as test data. The model is able to retrain over time and adapt to new modes when the operating conditions are changed. The model was tested on the IEEE-14 and IEEE-68 test systems, as well as on a 9-node fragment of a real system with actual measurements for 6 h with a frequency of 60 points per second. For synthetic models, the detection and recognition accuracy of the events averaged 97%.

The article [125] proposes an event classification algorithm for the real-time monitoring of the dynamic stability of the system using the PMU. The authors propose using the results of frequency measurements in individual nodes to calculate the indicator of dynamic stability of the generator nodes of the system—CRAS. This coefficient actually reflects the acceleration of the angles of the generator node relative to the center of inertia of the system, and the generator node k is calculated by the equation:

$$CRAS_k = \sum_{s=1}^{S} \left| \frac{\omega_k^s - \omega_k^{s-1}}{\Delta t} - \frac{\omega_{COI}^s - \omega_{COI}^{s-1}}{\Delta t} \right|, \tag{7}$$

where ω_k^s and ω_k^{s-1} are the angular velocities of the generator at node k, respectively, for consecutive measurements s and $s-1$, rad/s; Δt is the time difference of measurements s and $s-1$ from Phasor measurements, s; ω_{COI}^s и ω_{COI}^{s-1}—angular velocities at the center of inertia of the system, respectively, for successive measurements s and $s-1$, which for a system with N generators are defined as:

$$\omega_{COI}^s = \frac{\sum_{i=1}^{N} H_i \omega_i}{\sum_{i=1}^{N} H_i}, \tag{8}$$

where H_i—the inertia constant of the generator i, c; ω_i—the angular velocity of the generator i, rad/s.

Accordingly, if the CRAS turns out to be greater than zero, then an event is recorded in the system, and the greater this deviation, the more significant the disturbance in the network. A random forest algorithm is used to recognize events and classify them. The size of the sliding window for assessing the transient process is 18 cycles, and the time required for recognizing the event is 0.35 s. The measured values are the node voltages and their frequency. At the same time, the following four types of events are recognized: double short circuit with node shutdown, single short circuit with line shutdown, load shutdown, generation shutdown. During the computational experiment, 1456 scenarios for IEEE-39 and 4256 for IEEE-118 are used as a training sample. The accuracy of the recognition and classification of events using the proposed methodology reaches 97.95%, which is higher than for the other machine learning approaches with which the comparison is made: SVM—76.71%, kNN—77.05%, DT—93.49%. However, the authors did not check the robustness of the described algorithm and did not consider the case of working with low-quality data or with a sliding window smaller than the size. For this reason, the simulation results can be considered overly optimistic for real-world scenarios.

In [126], the authors consider the problem of the localization of forced oscillations and processing of Phasor measurements for their detection. It is known that such fluctuations can be triggered by large sharply variable loads, incorrect adjustments of the excitation regulators and the power systems stabilizer (PSS), and failures in the operation of the thermal part of stations and converters of renewable energy sources. The authors point out the problem associated with the fact that the source of vibrations can be very far from the installation site of the PMU, and, in this regard, they propose a method for its localization when the number of installed PMUs in the system is limited. To do this, it is proposed to use the robust principal component method and use it to perform the decomposition of the measurement matrix. The proposed technique uses only measurement data, does not require a dynamic model, and can identify sources of vibrations even in resonance conditions. Its real-time implementation is possible using the sliding window method. The algorithm was tested for the IEEE-68 and WECC-179 test models, and in 97% and 93% of cases, respectively, it gave the correct result. The accuracy of the identification depends on the width of the sliding window T_0, as shown in Figure 9. It is also strongly influenced by the quality of the data and the type of the measured parameter. Thus, when attempting to detect fluctuations only in the voltage modulus, the effectiveness of the technique will decrease by 10%, and when using only its phase, by 50%.

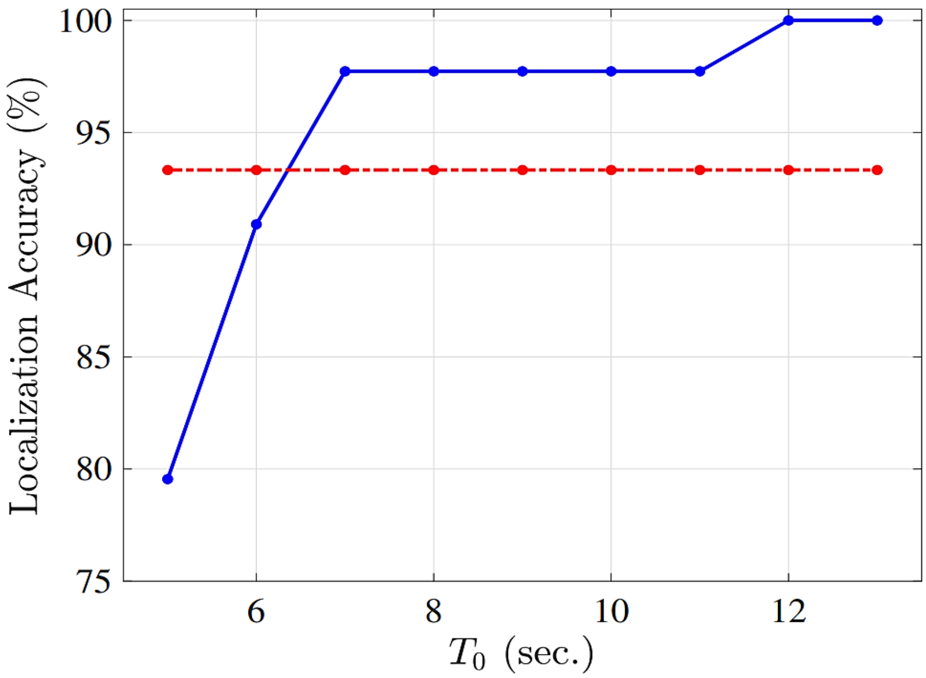

Figure 9. Accuracy of oscillation identification for IEEE-68 (blue line) and WECC-179 (red line) test systems [126].

The article [127] also proposes a two-stage method for evaluating the participation of generators in oscillatory modes in real time. First, the recognition of this type of mode is performed, at the second stage, the problem of their clustering is solved. In particular, there are groups of generators whose oscillations do not fade, or on the contrary, increase. For a sliding window, the length of which the authors propose to take as equal to 0.3 s, the prevailing type of oscillations for each generator is estimated using the matrix beam method. The initial data are measurements of the relative angles of the generator rotors from the PMU at the station. In the same step, the filtering of non-existing modes, noise, etc. is performed. Next, the clustering of generators is performed using the k-means method. At the same time, there are two categories of generators: self-oscillation/steady oscillations and damped oscillations. The use of clustering in this case is controversial since, in the first step of the procedure for evaluating the quality of oscillations of the oscillators of the generators of the system relative to each other, a quantitative assessment of this characteristic is already given.

In [128], a solution for identifying events based on the regional division of the system is proposed. The idea is to group the data from individual PMUs by areas of the power system and perform neural network training and clustering not for individual points of the network but for each of its areas separately, which should lead to lower computational costs and allow the use of the technique for real-time decision making. The k-means method is used for clustering the PMUs between the zones of the power system. In fact, the clustering criterion is the distance of the measurement points from each other, which the authors estimate by the difference in the measured voltage modules between different points of the network. Voltages and frequencies are considered as measured values, and the wavelet transform, the method of the characteristic ellipse, and image analysis are used to identify signs of events. The results of the first two approaches are used as a training sample for SVM, kNN, and DT. In the latter case, a convolutional neural network is trained for image analysis. The testing of the method for detecting event signs using wavelet transform when splitting the network by region was performed on a 68-node New England test model. At the same time, six categories of events were distinguished: line shutdown, voltage failure, generation shutdown, load shutdown, short circuit, and change in the operating mode of reactive power compensation means. The accuracy of event classification by all methods was high (more than 93%) and for the proposed approach reached 99.77%. In other words, in almost all scenarios, the method gave a reliable result, and this highlights the authors' insufficient attention to checking the operability of the solution with poor-quality data, changing the size of the sliding window, etc., and casts doubt on the results obtained.

According to the data presented in the paper, the group analysis of the Phasor measurement has multiple advantages in terms of calculation time, although it is associated with an additional error. Figure 10 shows the dependences of time and calculation errors on the number of selected regions of the power system.

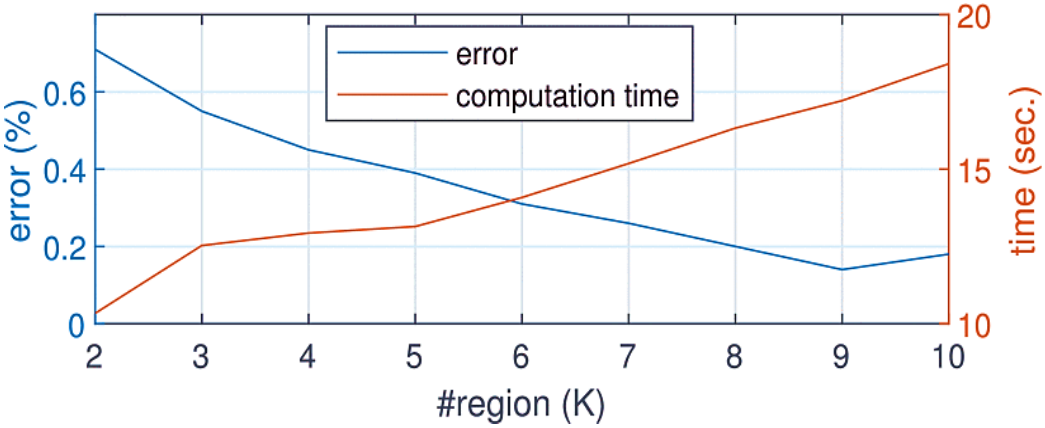

Figure 10. The accuracy of the classification of events depending on the number of Phasor measurements groups or zones of the power system [128].

In turn, the article [129] discusses the problem of using machine learning algorithms to solve emergency management problems for real power systems with insufficient data to form a training sample. The authors propose to use a learning mechanism to transfer and perform calculations for two network models: the basic model, for which there is redundant data for training, and the target model, which may have a different number of PMU installation points. Thus, the hypothesis is tested that the algorithm trained on the test model can be used to classify events in other networks. When training on test models, the cases of disconnections of lines and generators, short circuits, load disconnections, and transformer failures are considered. During the verification, computational experiments were carried out for the IEEE-14, Illinois-200, and South Carolina-500 models. For these models, training with transfer learning is performed in pairs at random PMU installation locations, and the ratio of their numbers for the base and target systems, respectively, is 8 to 1. Under these conditions, the average accuracy of event classification when using the proposed methodology reaches 81.7%.

The main trend in the development of event identification and classification is the use of machine learning methods. While deep neural networks, on average, achieve better results, a number of studies have also shown the effectiveness of simpler solutions, in particular, the SVM method. This is important because, as noted above, any PA system must recognize an event before implementing control actions. The integration of a simpler and more reliable auxiliary algorithm makes it possible to further reduce labor costs and simplify the system as a whole without a loss in quality.

Attention should be paid to the significant impact on the results of the origin of the training and test samples when checking the working ability of algorithms. The literature review in this article showed that, on average, working with synthetic data leads to higher accuracy of identification and classification tools. Accordingly, it is important to discuss overestimating estimates and the need for verification on real data. Among the methods of machine learning, transfer learning should be highlighted. This tool, with a limited size of the training sample, ensures high recognition accuracy.

Thus, when developing solutions aimed at identifying and classifying events in real time, it is necessary to take into account poor-quality measurements, because of which the accuracy of the systems can decrease dramatically; check the operation of algorithms on real measurements; not complicate algorithms and turn primarily to simple and proven solutions—such as the method SVM; with a small training sample, apply transfer learning and reduce the width of the sliding window when evaluating the transition process in the energy system.

The use of the Phasor measurements data to improve the algorithms of emergency control is one of the most promising and actively researched areas. First, this is due to the fact that the Phasor measurement data provide a more comprehensive understanding of the processes occurring in the power system, as a result of which it becomes possible to make more balanced and, in a certain sense, optimal decisions in terms of overcoming emergency events. At the same time, the collected or synthesized Phasor measurement data are excellent for experiments on the application of machine learning methods for power system management. On the one hand, such methods have the theoretical possibility of identifying non-visible dependencies in the available data, and such systems are theoretically able to work more efficiently than existing ones based on traditional, rigorous approaches. On the other hand, PMUs allow for the collection data on the state of the energy district as a whole, where it may not be so easy to identify some objective characteristics, and machine learning methods, by their nature, will be able to do this.

The use of the data obtained from PMUs for the task of managing the modes of EPS based on machine learning methods can be accompanied by several challenges associated with possible outliers, noise, and omissions in the source data. To overcome these issues, preprocessing of the received signals based on statistical analysis methods is used.

6. Determining the Optimal Installation Locations for PMUs

The task of determining the locations of PMUs, considering RES and distributed generation, is a complex problem of discrete optimization with a number of limitations in the form of equalities and inequalities [130]. The optimization problem of PMU device placement can be formulated as follows:

$$\sum_{i=1}^{N} k_i \to min, \tag{9}$$

where N—number of nodes EPS, k_i—indication of PMU installation in the node i.

Observability conditions can be written as linear constraints.

The following methods are used to solve this problem:

- Monte Carlo method [131–134];
- Methods of mathematical programming (integer linear programming, integer nonlinear programming, and integer quadratic programming) [135–138];
- Heuristic methods (genetic algorithm, search methods, and particle swarm optimization) [139–146].

The Monte Carlo method is based on the description of a mathematical model using a random number generator, in which multiple modeling is performed and the probabilistic characteristics of the process under consideration are calculated based on the data obtained. In [131], a probabilistic method for determining the merit of the PMU installation based on the Monte Carlo method was proposed. As an objective function, the sum of errors in estimating the values of the amplitude and phase of the voltage in the nodes of the EPS model was considered. The authors of the study [132] used the Monte Carlo method for the distribution network. For real-time application in the work [133], a hybrid approach for determining the location of PMU based on the Monte Carlo method and the analysis of the dynamic response of the EPS is proposed. The authors of the study [134] presented a method for determining the optimal location of PMUs, taking into account their cost and the cost of data transmission channels based on the Monte Carlo method.

Mathematical programming methods are understood as a class of methods aimed at solving optimization problems using linear and nonlinear methods. In [135], a multi-stage procedure based on linear programming was used for the optimal placement of PMUs in the EPS. Since the problem of optimal placement may not have a single solution, the authors developed indexes, with the help of which the ranking of the solutions found was performed. The study [136] is devoted to the development of a methodology for the optimal placement of PMU devices based on binary integer programming in combination with the heuristic approach developed by the authors. The authors of [137] considered the problem of the optimal placement of PMU devices in an isolated EPS based on the theory of binary linear integer programming. The effectiveness of the proposed method is demonstrated on the IEEE-7, IEEE-9, IEEE-14, and IEEE-30 test models. To improve the quality of state estimation in [138], a method for placing PMU devices based on the use of binary integer programming is considered. Testing of the proposed method was performed on the IEEE-14, IEEE-30, IEEE-39, and IEEE-57 models.

In [139], a genetic algorithm was used to ensure the observability of EPS due to PMUs. To identify harmonic distortions in [140], a method of PMU placement based on a genetic algorithm was proposed. The effectiveness of the method was demonstrated on the IEEE-60 model. In addition, the use of a genetic algorithm for the optimal placement of PMUs can be used for several purposes including determining damage in the power grid [141], assessing the static stability of the power grid [142], and determining the reverse direction of power in the distribution network [143]. The authors in [144] present a method of PMU placement using the search method. The proposed method can be used in systems with or without existing PMU devices. The method was tested on the IEEE-14, IEEE-30, and IEEE-57 models. The authors of the study [145] used binary particle swarm optimization to determine the PMU installation locations. In the study [146], a hybrid technique for placing PMU devices based on a quantum swarm of particles was proposed.

Furthermore, to determine the optimal placement of PMU devices, the methods of the Cuckoo optimization algorithm [147], binary bat algorithm [148], Discrete water cycle optimization [149], and Greedy algorithm [150] are used.

Identifying the optimal locations of PMU devices is an important task, which is reflected in the high interest among researchers. In the reviewed papers, three primary groups of methods were considered for PMU placement: the Monte Carlo method, mathematical programming methods, and heuristic methods (genetic algorithm, search methods, and particle swarm optimization). In solving the problem of optimizing PMU installation, various target functions are used that describe the amount of costs for PMUs and communication channels, providing the criterion for the observability of the EPS, minimizing the error of estimating the state, and more. Further research directions in the field of optimal PMU placement can be directed to the development of complex algorithms for emergency management and condition assessment tasks.

7. Conclusions

This work systematizes the latest developments and research devoted to the use of PMUs to solve three tasks: condition assessment, emergency management, and the implementation of emergency protection of power systems. Based on the results of the analysis for each of the directions, it is possible to come to certain conclusions.

In terms of relay protection, the areas of improvement for its functions are based primarily on the capabilities of modern PMUs and devices for processing these measurements—APDC. Phasor measurement technologies are being developed in a cascading manner, in which the expansion of their application leads to an increase in the number of devices, which in turn expands the range of tasks to be solved.

The most demanded advantages of using Phasor measurement in protection are the possibilities of significantly expanding the scope of their application in traditional algorithms as well as the qualitative improvement of their characteristics, in particular, the comprehensive introduction into the operation of long-range redundancy stages of step-by-step protections with reduced time exposures and the possibility of organizing protections with a wide coverage of connections based on the differential principle, which is relevant primarily for distribution networks. In addition, an investment-attractive direction is the development of new starting bodies for the protection of network elements (especially electric transmission lines), analyzing the form of changes in operating parameters, which allows you to abandon the use of communication channels. However, this direction is still conceptual.

On the other hand, there are a number of limitations for the use of PMUs not only in relay protection but also in other control systems. The most significant of them are related to cybersecurity and the development of standards in the field of measurements. The issues of data transmission through communication channels and storage and the processing of large volumes of measurements can be attributed an average degree of importance.

In the task of assessing the state, the introduction of new types of measuring complexes opens up broad prospects. Based on the use of only Phasor measurement, the SE problem becomes linear and is reduced to a one-time solution of a system of linear equations. On the other hand, the inclusion of Phasor measurement in the SE task entails some computational difficulties and forces the modification of existing program complexes and algorithms used in them. The high cost of PMU implementation at power system facilities will not allow us to come to a linear SE only on their basis in the near future. In the most optimistic case, such a transition will lead to a large number of critical measurements, which are extremely undesirable, especially in terms of stress angles. Despite the solution of a number of problems aimed at using information from the PMUs in the SE task, this area has extensive potential for research. For example, the question of choosing the method of accounting for classical telemetry together with vector measurements remains open. In addition, some solutions to the existing problems of using PMU data in the SE are built on a compromise, in the course of further research, more effective alternatives may be proposed for them.

The development of emergency automation based on Phasor measurement is also promising. Despite positive results that have been obtained in many of the considered works in this area, the vast majority of studies are based on synthetic data of the Phasor measurement obtained during mathematical modeling. In general, within the theory of machine learning, the task of transferring learning is one of the most urgent today. As a result, it is impossible to predict the quality of the proposed systems in a single way when they are applied in practice using real data. The only direction for which results based on real data have been published is for the task of classifying events. Accordingly, the further development of emergency management systems should be aimed at the application of methods based on real or approximate data. At the same time, the interest in various kinds of control systems corresponds to the peculiarities of the operation of trunk and distribution networks.

In the works devoted to the analysis of transients, it is assumed that the PMU devices are located at all generating nodes within the energy district under consideration. Accordingly, the active implementation of PMU-based control algorithms will become possible only after the wider dissemination of these devices. The second limitation is more related to methods based on machine learning technologies and is associated with a subjective distrust of such approaches. Indeed, since trained models are often difficult to interpret, it is impossible to predict unequivocally what decision will be made in a given situation and for what reason. This has caused the existing skepticism, which can be resolved by applying more stringent requirements and criteria at the implementation stage.

For the modern EPS with a significant share of RES, low inertia, distributed generation sources, and the introduction of digital protection and monitoring systems, the use of PMUs as a source of accurate measurements is significant. PMUs allow for the monitoring of the voltage phase at each point of the power plant, which makes it possible to build adaptive algorithms for emergency control that can provide the necessary speed characteristics for transient processes in low-inertia power units [151,152]. The development and implementation of new PMU algorithms that provide an assessment of synchrophasors with a delay of less than the period of the industrial frequency [153,154] create an opportunity to assess the location and type of disturbance in the EPS, which is especially important for solving transient monitoring tasks.

Based on the above review, it is obvious that there is a clear need to increase the number of intelligent monitoring and control systems of established and transient processes in the modern EPS. The prerequisites for the above are a change in the EPS transients, a change in the functioning of electricity markets, and a reduction in the cost of PMU devices. Table 1 shows the directions for future research in the field of PMU application for the monitoring and control of the EPS.

Table 1. Directions of research for the use of PMUs for monitoring and control of the EPS.

Direction	Possible Solutions	Prerequisites
Emergency control	Development of adaptive algorithms implementing emergency control based on machine learning methods capable of forming an optimal impact on the EPS at the pace of the transition process	An increase in the rate of transient processes due to a decrease in the inertia of the EPS
Relay protection	Development of adaptive relay protection systems that provide selective shutdown of a damaged element of the EPS in the presence of a significant share of RES	Increasing the stochasticity of normal and transient processes of EPS
SE	Increasing the speed and accuracy of condition assessments	The need to increase the speed and accuracy of the assessment of the state
Optimal PMU placement	Development of complex algorithms for optimal PMU placement for emergency control and condition assessment tasks	The need to reduce the load of communication channels from PMU to APDC, ensuring the observability of the EPS
Development of algorithms for determining synchrophasors	Development of accelerated methods for determining a synchrophasors with a delay of less than a period of industrial frequency	An increase in the rate of transient processes due to a decrease in the inertia of the EPS

As shown in Table 1, there exists an extensive range of research areas for the use of PMUs in the tasks of monitoring and controlling an EPS. To date, the introduction of PMUs remains a rather expensive measure to ensure the observability of EPS. Before the introduction of a PMU, a technical and economic analysis should be carried out, which consists of calculating the benefits obtained from the introduction of the PMU device in the selected node of the EPS in terms of reducing the under-supply of electricity to consumers through the introduction of new algorithms for emergency management and increasing the possible capacity of the electrical network due to more accurate monitoring of transient processes.

In most of the works considered, the algorithms were tested on synthetic data obtained during modeling of mathematical models of the EPS. Therefore, an important direction is the approbation of algorithms in real EPSs or on physical models [153]. Most of the works considered are theoretical in nature. Barriers to their practical implementation include the lack of standards that allow the use of adaptive algorithms for emergency management and monitoring based on PMUs in real power systems and a small number of installed PMUs.

Furthermore, one of the directions of future work is to refine the standard for the development of PMU algorithms [155,156] in terms of dynamic responses and delays in obtaining an estimate of synchrophasors for low-inertia EPSs in the presence of RES and distributed generations.

Author Contributions: All authors have made valuable contributions to this paper. Conceptualization, A.P. and I.Z.; methodology, A.P. and M.S. (Mihail Senyuk); software, A.P. and P.G.; validation, I.P., N.M. and I.Z.; formal analysis, F.K., A.P. and P.G.; investigation, A.P., M.S. (Murodbek Safaraliev), I.P., P.G., I.Z. and F.K.; writing—original draft preparation, A.P., P.G., I.P. and I.Z.; writing—review and editing, M.S. (Murodbek Safaraliev) and I.Z.; supervision, F.K., M.S. (Murodbek Safaraliev) and I.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The reported study was supported by Russian Science Foundation, research project № 23-79-01024.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AESM	Automatic elimination of asynchronous mode
AER	Automatic excitation regulator
AFLS	Automatic frequency load shedding
AI	Artificial intelligence
ANN	Artificial neural networks
APDC	Advanced phasor data concentrato
AVR	Automatic voltage regulator
CLTL	Cross-lingual transfer learning
DFT	Discrete Fourier transformation
DS	Digital substation
DT	Decision tree
DWT	Discrete wavelet transform
ECA	Emergency control automatics
ECS	Electrical centre of swings
EPS	Electric power substation
FACTS	Flexible alternating current transmission system
FFNN	Feedforward neural network
HT	Hilbert transformation
IEEE	Institute of electronic and electrical engineers
iNNE	Isolation using Nearest Neighbor Ensemble
kNN	K-nearest neighbor method
LR	Lock-out relay
LSM	Least square method
MC-CNN	Multi-channel convolutional neural network
MLP	Multilayer perceptron
MLR	Multinomial logistic regression
OOSPD	Out-of-step protection device
OP	Overcurrent protection
PMU	Phasor measurement unit
POW	Point of Wave
PS	Power system

PSS	Power system stabilizer
RES	Renewable energy resources
SB	Swing blocking
SC	Short circuit
SCADA	Supervisory control and data acquisition system
SC-CNN	Single channel convolutional neural network
SKNNO	kNN method with reinforcement
SE	State estimation
SCB	Static capacitor bank
SVM	Support vector machine
SLE	System of linear equations
WAMPAC	Wide Area Monitoring Protection and Control
WLSM	Weighted least squares method

References

1. Liu, D.; Zhang, X.; Tse, C.K. Effects of High Level of Penetration of Renewable Energy Sources on Cascading Failure of Modern Power Systems. *IEEE J. Emerg. Sel. Top. Circuits Syst.* **2022**, *12*, 98–106. [CrossRef]
2. Hu, J.; Liu, X.; Shahidehpour, M.; Xia, S. Optimal Operation of Energy Hubs with Large-Scale Distributed Energy Resources for Distribution Network Congestion Management. *IEEE Trans. Sustain. Energy* **2021**, *12*, 1755–1765. [CrossRef]
3. Xu, S.; Liu, H.; Bi, T.; Martin, K.E. A High-Accuracy Phasor Estimation Algorithm for PMU Calibration and Its Hardware Implementation. *IEEE Trans. Smart Grid* **2020**, *11*, 3372–3383. [CrossRef]
4. Plamanescu, R.; Albu, M.; Gheorghe, S.; Bugnar, S.; Coroiu, M. PMU Cloud-based Applications for Power Systems Insight. In Proceedings of the 2019 54th International Universities Power Engineering Conference (UPEC), Bucharest, Romania, 3–6 September 2019; pp. 1–5. [CrossRef]
5. Baudette, M.; Vanfretti, L.; Del-Rosario, G.; Ruíz-Alvarez, A.; Domínguez-García, J.L.; Al-Khatib, I. Validating a real-time PMU-based application for monitoring of sub-synchronous wind farm oscillations. In Proceedings of the ISGT 2014, Washington, DC, USA, 19–22 February 2014; pp. 1–5. [CrossRef]
6. Liu, X.; Nair, N.-K.C. Review on D-PMU based applications for active electricity distribution system. In Proceedings of the 2020 IEEE International Conference on Power Systems Technology (POWERCON), Bangalore, India, 14–16 September 2020; pp. 1–6. [CrossRef]
7. Wang, X.; Lu, N.; Luo, H. Optimization Based Distribution Network Fault Location Method Using PMU Information. In Proceedings of the 2022 China International Conference on Electricity Distribution (CICED), Changsha, China, 7–8 September 2022; pp. 1361–1365. [CrossRef]
8. Hou, Y.; Fang, T.; Shi, F.; Zhang, H. Parameter estimation method of distribution network based on PMU measurement data. In Proceedings of the 2020 5th Asia Conference on Power and Electrical Engineering (ACPEE), Chengdu, China, 4–7 June 2020; pp. 1620–1625. [CrossRef]
9. Alinejad, B.; Akbari, M.; Kazemi, H. PMU-based distribution network load modelling using Harmony Search Algorithm. In Proceedings of the 2012 17th Conference on Electrical Power Distribution, Tehran, Iran, 2–3 May 2012; pp. 1–6.
10. Mogharbel, B.; Fan, L.; Miao, Z. Least squares estimation-based synchronous generator parameter estimation using PMU data. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015; pp. 1–5. [CrossRef]
11. Satsuk, E.; Zhukov, A.; Dubinin, D.; Ivanov, I.; Murzin, A. Analytical Approach to Phasor-based Line Parameter Estimation Verified Through Real PMU Data. In Proceedings of the 2022 International Conference on Smart Grid Synchronized Measurements and Analytics (SGSMA), Split, Croatia, 24–26 May 2022; pp. 1–6. [CrossRef]
12. Chowdhury, S.D.; Senroy, N. PMU data based online parameter estimation of synchronous generator. In Proceedings of the 2016 IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, 4–6 March 2016; pp. 1–6. [CrossRef]
13. Rahman, K.M.J.; Munnee, M.M.; Khan, S. Largest blackouts around the world: Trends and data analyses. In Proceedings of the 2016 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE), Pune, India, 19–21 December 2016; pp. 155–159. [CrossRef]
14. Phadke, A.G. Synchronized phasor measurements-a historical overview. In Proceedings of the IEEE/PES Transmission and Distribution Conference and Exhibition, Yokohama, Japan, 6–10 October 2002; Volume 1, pp. 476–479. [CrossRef]
15. Xu, S.; Liu, H.; Bi, T. Field PMU Test and Calibration Method—Part I: General Framework and Algorithms for PMU Calibrator. *J. Mod. Power Syst. Clean Energy* **2022**, *10*, 1507–1518. [CrossRef]
16. Castello, P.; Ferrero, R.; Pegoraro, P.A.; Toscani, S. Effect of Unbalance on Positive-Sequence Synchrophasor, Frequency, and ROCOF Estimations. *IEEE Trans. Instrum. Meas.* **2018**, *67*, 1036–1046. [CrossRef]
17. Wen, H.; Teng, Z.; Wang, Y.; Yang, Y. Optimized Trapezoid Convolution Windows for Harmonic Analysis. *IEEE Trans. Instrum. Meas.* **2013**, *62*, 2609–2612. [CrossRef]
18. Derviškadić, A.; Romano, P.; Paolone, M. Iterative-Interpolated DFT for Synchrophasor Estimation: A Single Algorithm for P- and M-Class Compliant PMUs. *IEEE Trans. Instrum. Meas.* **2018**, *67*, 547–558. [CrossRef]

19. Romano, P.; Paolone, M. Enhanced Interpolated-DFT for Synchrophasor Estimation in FPGAs: Theory, Implementation, and Validation of a PMU Prototype. *IEEE Trans. Instrum. Meas.* **2014**, *63*, 2824–2836. [CrossRef]
20. Romano, P.; Paolone, M. An enhanced interpolated-modulated sliding DFT for high reporting rate PMUs. In Proceedings of the 2014 IEEE International Workshop on Applied Measurements for Power Systems Proceedings (AMPS), Aachen, Germany, 24–26 September 2014; pp. 1–6. [CrossRef]
21. Belega, D.; Petri, D. Accuracy of synchrophasor measurements provided by the sine-fit algorithms. In Proceedings of the 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), Florence, Italy, 9–12 September 2012; pp. 921–926. [CrossRef]
22. Balestrieri, E.; De Vito, L.; Rapuano, S.; Slepicka, D. Estimating the Uncertainty in the Frequency Domain Characterization of Digitizing Waveform Recorders. *IEEE Trans. Instrum. Meas.* **2012**, *61*, 1613–1624. [CrossRef]
23. Karimi-Ghartemani, M.; Ooi, B.-T.; Bakhshai, A. Application of Enhanced Phase-Locked Loop System to the Computation of Synchrophasors. *IEEE Trans. Power Deliv.* **2011**, *26*, 22–32. [CrossRef]
24. Yang, H.; Tu, Y.; Peng, Y. Comparative analysis of phase difference estimation methods based on Hilbert transform with or without endpoint effect. In Proceedings of the 2020 39th Chinese Control Conference (CCC), Shenyang, China, 27–29 July 2020; pp. 2963–2967. [CrossRef]
25. Martin, K.E.; Hamai, D.; Adamiak, M.G.; Anderson, S.; Begovic, M. Exploring the IEEE Standard C37.118–2005 Synchrophasors for Power Systems. *IEEE Trans. Power Deliv.* **2008**, *23*, 1805–1811. [CrossRef]
26. de la O Serna, J.A. Dynamic phasor estimates for power system oscillations and transient detection. In Proceedings of the 2006 IEEE Power Engineering Society General Meeting, Montreal, QC, Canada, 18–22 June 2006; p. 7. [CrossRef]
27. Frigo, G.; Derviškadić, A.; Zuo, Y.; Bach, A.; Paolone, M. Taylor-Fourier PMU on a Real-Time Simulator: Design, Implementation and Characterization. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 23–27 June 2019; pp. 1–6. [CrossRef]
28. de la O Serna, J.A. Synchrophasor Estimation Using Prony's Method. *IEEE Trans. Instrum. Meas.* **2013**, *62*, 2119–2128. [CrossRef]
29. Toscani, S.; Muscas, C.; Pegoraro, P.A. Design and Performance Prediction of Space Vector-Based PMU Algorithms. *IEEE Trans. Instrum. Meas.* **2017**, *66*, 394–404. [CrossRef]
30. Al-Othman, A.K.; Irving, M.R. A comparative study of two methods for uncertainty analysis in power system State estimation. *IEEE Trans. Power Syst.* **2005**, *20*, 1181–1182. [CrossRef]
31. Tarali, A.; Abur, A. Bad data detection in two-stage state estimation using phasor measurements. In Proceedings of the 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin, Germany, 14–17 October 2012; pp. 1–8. [CrossRef]
32. Chen, J.; Abur, A. Improved bad data processing via strategic placement of PMUs. In Proceedings of the IEEE Power Engineering Society General Meeting 2005, San Francisco, CA, USA, 16 June 2005; pp. 2759–2763. [CrossRef]
33. Göl, M.; Abur, A. LAV Based Robust State Estimation for Systems Measured by PMUs. *IEEE Trans. Smart Grid* **2014**, *5*, 1808–1814. [CrossRef]
34. Göl, M.; Abur, A. A Hybrid State Estimator for Systems with Limited Number of PMUs. *IEEE Trans. Power Syst.* **2015**, *30*, 1511–1517. [CrossRef]
35. Kolosok, I.N.; Korkina, E.S.; Mahnitko, A.E. Detection of systematic errors in PMU measurements by the power system state estimation methods. In Proceedings of the 2015 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 14 October 2015; pp. 1–4. [CrossRef]
36. Zhang, J.; Welch, G.; Bishop, G.; Huang, Z. A Two-Stage Kalman Filter Approach for Robust and Real-Time Power System State Estimation. *IEEE Trans. Sustain. Energy* **2014**, *5*, 629–636. [CrossRef]
37. Ghahremani, E.; Kamwa, I. Dynamic State Estimation in Power System by Applying the Extended Kalman Filter with Unknown Inputs to Phasor Measurements. *IEEE Trans. Power Syst.* **2011**, *26*, 2556–2566. [CrossRef]
38. Zivanovic, R.; Cairns, C. Implementation of PMU technology in state estimation: An overview. In Proceedings of the IEEE. AFRICON '96, Stellenbosch, South Africa, 27 September 1996; Volume 2, pp. 1006–1011. [CrossRef]
39. Manousakis, N.M.; Korres, G.N. Optimal PMU Placement for Numerical Observability Considering Fixed Channel Capacity—A Semidefinite Programming Approach. *IEEE Trans. Power Syst.* **2016**, *31*, 3328–3329. [CrossRef]
40. Gao, Z.; Li, J. Optimal PMU Placement Considering Data Integrity Attack. In Proceedings of the 2022 IEEE 16th International Conference on Compatibility, Power Electronics, and Power Engineering (CPE-POWERENG), Birmingham, UK, 29 June–1 July 2022; pp. 1–5. [CrossRef]
41. Zhou, M.; Centeno, V.A.; Thorp, J.S.; Phadke, A.G. An Alternative for Including Phasor Measurements in State Estimators. *IEEE Trans. Power Syst.* **2006**, *21*, 1930–1937. [CrossRef]
42. Phadke, A.G.; Thorp, J.S.; Nuqui, R.F.; Zhou, M. Recent developments in state estimation with phasor measurements. In Proceedings of the 2009 IEEE/PES Power Systems Conference and Exposition, Seattle, WA, USA, 15–18 March 2009; pp. 1–7. [CrossRef]
43. Yang, T.; Sun, H.; Bose, A. Transition to a Two-Level Linear State Estimator—Part I: Architecture. *IEEE Trans. Power Syst.* **2011**, *26*, 46–53. [CrossRef]
44. Yang, T.; Sun, H.; Bose, A. Transition to a Two-Level Linear State Estimator—Part II: Algorithm. *IEEE Trans. Power Syst.* **2011**, *26*, 54–62. [CrossRef]
45. Joshi, P.M.; Verma, H. Synchrophasor measurement applications and optimal PMU placement: A review. *Electr. Power Syst. Res.* **2021**, *199*, 107428. [CrossRef]

46. Zhu, J.; Abur, A. Effect of Phasor Measurements on the Choice of Reference Bus for State Estimation. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–5. [CrossRef]
47. D'Antona, G.; Davoudi, M. Effect of Phasor Measurement Unit on power State Estimation considering parameters uncertainty. In Proceedings of the 2012 IEEE International Workshop on Applied Measurements for Power Systems (AMPS) Proceedings, Aachen, Germany, 26–28 September 2012; pp. 1–5. [CrossRef]
48. Mokeev, A.V.; Piskunov, S.A. Expanding the Field of Synchronized Phasor Measurements Application in Power Systems. In Proceedings of the 2021 International Siberian Conference on Control and Communications (SIBCON), Kazan, Russia, 13–15 May 2021; pp. 1–6. [CrossRef]
49. Patil, G.C.; Thosar, A.G. Application of synchrophasor measurements using PMU for modern power systems monitoring and control. In Proceedings of the 2017 International Conference on Computation of Power, Energy Information and Commuincation (ICCPEIC), Melmaruvathur, India, 22–23 March 2017; pp. 754–760. [CrossRef]
50. Zhao, J.; Zhang, G.; Jabr, R.A. Robust Detection of Cyber Attacks on State Estimators Using Phasor Measurements. *IEEE Trans. Power Syst.* **2017**, *32*, 2468–2470. [CrossRef]
51. Ahmad, F.A.; Habiballah, I.O.; Shahriar, M.S. Inclusion of Phasor Measurement Units in Least Measurement Rejected State Estimator. In Proceedings of the 2018 Australasian Universities Power Engineering Conference (AUPEC), Auckland, New Zealand, 27–30 November 2018; pp. 1–7. [CrossRef]
52. Ghosh, P.K. Complete and incomplete PMU observablity for hybrid state estimation. In Proceedings of the 2017 International Conference on Computation of Power, Energy Information and Commuincation (ICCPEIC), Melmaruvathur, India, 22–23 March 2017; pp. 867–870. [CrossRef]
53. Kumar, J.; Rai, J.N.; Hasan, N. Use of Phasor Measurement Unit (PMU) for large scale power system state estimation. In Proceedings of the 2012 IEEE 5th India International Conference on Power Electronics (IICPE), Delhi, India, 6–8 December 2012; pp. 1–5. [CrossRef]
54. Abur, A.; Gomez-Exposito, A. *Power System State Estimation: Theory and Implementation*; CRC Press: Boca Raton, FL, USA, 2004; Volume 24. [CrossRef]
55. De la Villa Jaén, A.; Martínez, J.B.; Gómez-Expósito, A.; Vázquez, F.G. Tuning of Measurement Weights in State Estimation: Theoretical Analysis and Case Study. *IEEE Trans. Power Syst.* **2018**, *33*, 4583–4592. [CrossRef]
56. Baltensperger, R.; Loosli, A.; Sauvain, H.; Zima, M.; Andersson, G.; Nuqui, R. An implementation of two-stage hybrid state estimation with limited number of PMU. In Proceedings of the 10th IET International Conference on Developments in Power System Protection (DPSP 2010), Manchester, UK, 29 March–1 April 2010; pp. 1–5. [CrossRef]
57. Zhong, S.; Abur, A. Auto tuning of measurement weights in WLS state estimation. *IEEE Trans. Power Syst.* **2004**, *19*, 2006–2013. [CrossRef]
58. Zhang, L.; Abur, A. State estimator tuning for PMU measurements. In Proceedings of the 2011 North American Power Symposium, Boston, MA, USA, 4–6 August 2011; pp. 1–4. [CrossRef]
59. *Standart 56947007-29.120.70.241-2017*; Technical Requirements for Microprocessor-Based Relay Protection. FGC UES, PJSC Standard; Date of Changes Introduction: 11.12.2019; FSK-Rosseti PAO: Moscow, Russia, 2017; 357p.
60. Ramesh, L.; Chowdhury, S.P.; Chowdhury, S. Wide area monitoring protection and control—A comprehensive application review. In Proceedings of the 10th International Conference on Developments in Power System Protection (DPSP 2010), Managing the Change, Manchester, UK, 29 March–1 April 2010; IET: London, UK; pp. 1–4. [CrossRef]
61. Khederzadeh, M. Wide-area protection in smart grids. In Proceedings of the 11th IET International Conference on Developments in Power Systems Protection (DPSP 2012), Birmingham, UK, 23–26 April; IET: London, UK, 2012; pp. 1–4. [CrossRef]
62. Leibovich, P.; Issouribehere, F.; Barbero, J. Design and Implementation of a low-cost PMU: Validation by tests and performance during 2019 Argentinean blackout. In Proceedings of the IEEE Power & Energy Society General Meeting (PESGM 2021), Washington, DC, USA, 26–29 July 2021; pp. 1–5. [CrossRef]
63. Chavez, J.J.; Kumar, N.V.; Azizi, S.; Guardado, J.L.; Rueda, J.; Palensky, P.; Terzija, V.; Popov, M. PMU-voltage drop based fault locator for transmission backup protection. *Electr. Power Syst. Res.* **2021**, *196*, 107188. [CrossRef]
64. Motavalian, A.R.; Moadabi, N.; Gharehpetian, G.B. Reliability Assessment of Power System Backup Protection in Smart Grid Control Center Using Phasor Measurement Units (PMU). *Renew. Energy Power Qual. J.* **2013**, *11*, 404–410. [CrossRef]
65. Karthick, S.; Lakshmi, K. Wide area backup protection scheme for power transmission lines using PMU. *Int. Res. J. Eng. Technol. IRJET* **2015**, *2*, 273–281.
66. Jena, M.K.; Samantaray, S.R.; Panigrahi, B.K. Supervisory control based wide area back-up protection scheme for power transmission network. In Proceedings of the National Power Systems Conference (NPSC 2016), Bhubaneswar, India, 19–21 December 2016; pp. 1–5. [CrossRef]
67. Saran, A. Comparison between overcurrent relay and devel-oped PMU based protection. In Proceedings of the North American Power Symposium (NAPS 2013), Manhattan, KS, USA, 22–24 September 2013; pp. 1–6. [CrossRef]
68. Rao, J.G.; Pradhan, A.K. Application of synchrophasor data for fault detection during power swing. In Proceedings of the International Conference on Energy, Automation and Signal, Bhubaneswar, India, 28–30 December 2011; pp. 1–5. [CrossRef]
69. Ariff, M.A.M.; Pal, B.C. Adaptive Protection and Control in the Power System for Wide-Area Blackout Prevention. *IEEE Trans. Power Deliv.* **2016**, *31*, 1815–1825. [CrossRef]

70. Keramat, M.M.; Fazaeli, M.H. The New Adaptive Protection Method for the Compensated Transmission Lines with the Series Capacitor in a High Share of Wind Energy Resources by Using PMU Data. In Proceedings of the 7th Iran Wind Energy Conference (IWEC 2021), Shahrood, Iran, 17–18 May 2021; pp. 1–6. [CrossRef]
71. Sarangi, S.; Pradhan, A.K. Apply PMU data for Zone-2 setting of series compensated line. In Proceedings of the International Conference on Energy, Automation and Signal, Bhubaneswar, India, 28–30 December 2011; pp. 1–6. [CrossRef]
72. Pal, D.; Mallikarjuna, B.; Reddy, R.J.; Reddy, M.J.B.; Mohanta, D.K. Synchrophasor Assisted Adaptive Relaying Methodology to Prevent Zone-3 Mal-Operation During Load Encroachment. *IEEE Sens. J.* **2017**, *17*, 7713–7722. [CrossRef]
73. Naeini, E.; Vaseghi, B.; Mahdavian, M. Modified Transmission Line Protection Scheme in the Presence of SCC. *J. Electr. Eng. Technol.* **2017**, *12*, 533–540. [CrossRef]
74. Chunju, F.; Shengfang, L.; Weiyong, Y.; Li, K.K. Study on adaptive relay protection scheme based on phase measurement unit (PMU). In Proceedings of the Eighth IEE International Conference on Developments in Power System Protectio, Amsterdam, The Netherlands, 5–8 April 2004; IET: London, UK, 2004; pp. 36–39. [CrossRef]
75. Yang, Z.; Liao, W.; Zhang, Q.; Bak, C.L.; Chen, Z. Fault Coordination Control for Converter-Interfaced Sources Compatible With Distance Protection During Asymmetrical Faults. *IEEE Trans. Ind. Electron.* **2023**, *70*, 6941–6952. [CrossRef]
76. Bi, T.; Sui, J.; Yu, H.; Yang, Q. Adaptive loss of field protection based on phasor measure-ments. In Proceedings of the IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–4. [CrossRef]
77. Senapati, S.; Das Bhattacharya, K.; Das, J.K. Application of phasor measurement unit in adaptive protection for loss of excitation in a generator. In Proceedings of the 6th IEEE Power India International Conference (PIICON 2014), Delhi, India, 5–7 December 2014; pp. 1–5. [CrossRef]
78. Desai, J.P.; Makwana, V.H. Phasor Measurement Unit Incorporated Adaptive Out-of-step Protection of Synchronous Generator. *J. Mod. Power Syst. Clean Energy* **2021**, *9*, 1032–1042. [CrossRef]
79. Dragomir, I.-M.; Iliescu, S.S. Synchrophasors Applications in Power System Monitoring, Protection and Control. In Proceedings of the 2015 20th International Conference on Control Systems and Computer Science, Bucharest, Romania, 27–29 May 2015; pp. 978–983. [CrossRef]
80. Skok, S.; Frlan, K.; Ugarkovic, K. Detection and Protection of Distributed Generation from Island Operation by Using PMUs. *Energy Procedia* **2017**, *141*, 438–442. [CrossRef]
81. Xu, M.; Meng, T.; Zou, G.; Zhang, J.; Lin, X.; Yang, J. A centralized protection and control scheme for microgrid. In Proceedings of the 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC 2015), Brisbane, QLD, Australia, 15–18 November 2015; pp. 1–5. [CrossRef]
82. Follum, J.; Miller, L.; Etingov, P.; Kirkham, H.; Riepnieks, A.; Fan, X.; Ellwein, E. *Phasor or Waveforms: Considerations for Choosing Measurements to Match Your Application*; Pacific Northwest Report; Pacific Northwest National Laboratory: Richland, WA, USA, 2021; 43p.
83. Galvez, C.; Abur, A. Fault Location in Meshed and Active Power Distribution Networks. In Proceedings of the IEEE Madrid PowerTech, Madrid, Spain, 28 June–2 July 2021; pp. 1–6. [CrossRef]
84. Chusovitin, P.V.; Vershinin, A.B. Emergency control system for angular stability based on PMU data. In Proceedings of the 2021 4th International Youth Scientific and Technical Conference on Relay Protection and Automation (RPA), Moscow, Russia, 21–22 October 2021; pp. 1–9. [CrossRef]
85. Yang, Y.; Shu, H. Power system stability analysis and control based on PMU. In Proceedings of the 2011 International Conference on Computer Science and Service System (CSSS), Nanjing, China, 27–29 June 2011; pp. 3376–3379. [CrossRef]
86. Li, H.; Xie, X.; Tong, L.; Wu, J.; Luo, J. Implement of On-line Transient Stability Control Pre-decision in Wide-Area Measurement System in Jiangsu Power Network. In Proceedings of the 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific, Dalian, China, 18 August 2005; pp. 1–4. [CrossRef]
87. Das, H.P.; Pradhan, A.K. Development of a micro-phasor measurement unit for distribution system applications. In Proceedings of the 2016 National Power Systems Conference (NPSC), Bhubaneswar, India, 19–21 December 2016; pp. 1–5. [CrossRef]
88. Boussadia, F.; Belkhiat, S. A new adaptive underfrequency load shedding scheme to improve frequency stability in electric power system. *J. Eur. Des Systèmes Autom.* **2021**, *54*, 263–271. [CrossRef]
89. Eissa, M.M.; Ali, A.A.; Abdel-Latif, K.; Al-Kady, A.F. A frequency control technique based on decision tree concept by managing thermostatically controllable loads at smart grids. *Int. J. Electr. Power Energy Syst.* **2019**, *108*, 40–51. [CrossRef]
90. Shekari, T.; Gholami, A.; Aminifar, F.; Sanaye-Pasand, M. An Adaptive Wide-Area Load Shedding Incorporating Power System Real-Time Limitations. *IEEE Syst. J.* **2018**, *12*, 759–767. [CrossRef]
91. Zhu, Q. A Deep End-to-End Model for Transient Stability Assessment with PMU Data. *IEEE Access* **2018**, *6*, 65474–65487. [CrossRef]
92. Zhang, Y.; Zhang, S.; Wang, J. A power system out-of-step splitting control system based on wide area information and an on-line searching scheme of optimal splitting section. *Int. J. Electr. Power Energy Syst.* **2021**, *126*, 106587. [CrossRef]
93. Nguyen, N.-V.; Shin, V.; Shevlyakov, G. Power system state estimation with fusion method. In Proceedings of the 2nd International Conference on Computer and Automation Engineering (ICCAE), Singapore, 26–28 February 2010; pp. 71–76. [CrossRef]
94. Zhang, S.; Zhang, Y. A Novel Out-of-Step Splitting Protection Based on the Wide Area Information. *IEEE Trans. Smart Grid* **2017**, *1*, 41–51. [CrossRef]

95. Aghamohammadi, M.; Abedi, M. DT based intelligent predictor for out of step condition of generator by using PMU data. *Int. J. Electr. Power Energy Syst.* **2018**, *99*, 95–106. [CrossRef]
96. Ivankovi, I.; Kuzle, I.; Holjevac, N. Wide Area Information-Based Transmission System Centralized Out-of-Step Protection Scheme. *Energies* **2017**, *10*, 633. [CrossRef]
97. Tealane, M.; Kilter, J.; Popov, M.; Bagleybter, O.; Klaar, D. Online Detection of Out-of-Step Condition Using PMU-Determined System Impedances. *IEEE Access* **2022**, *10*, 14807–14818. [CrossRef]
98. Deshmukh, B.; Biswal, S.; Lal, D.K. Synchronous Generator Out-of-Step Protection Based on Savitzky-Golay Filtering Technique. In Proceedings of the 2021 Emerging Trends in Industry 4.0 (ETI 4.0), Raigarh, India, 19–21 May 2021; pp. 1–3. [CrossRef]
99. Zare, H.; Alinejad-Beromi, Y.; Yaghobi, H. Intelligent prediction of out-of-step condition on synchronous generators because of transient instability crisis. *Int. Trans. Electr. Energy Syst.* **2018**, *29*, 2686. [CrossRef]
100. Mahdi, M.; Genc, V.M.I. A Real-Time Self-Healing Methodology Using Model- and Measurement-Based Islanding Algorithms. *IEEE Trans. Smart Grid* **2019**, *10*, 1195–1204. [CrossRef]
101. Shukla, A.; Dutta, S.; Sadhu, P.K. An island detection approach by μ-PMU with reduced chances of cyber-attack. *Int. J. Electr. Power Energy Syst.* **2021**, *126*, 106599. [CrossRef]
102. Chatterjee, S.; Roy, B. Bagged tree based anti-islanding scheme for multi-DG microgrids. *J. Ambient. Intell. Humaniz. Comput.* **2021**, *12*, 2273–2284. [CrossRef]
103. Tang, Y.; Li, F.; Zheng, C.; Wang, Q.; Wu, Y. PMU Measurement-Based Intelligent Strategy for Power System Controlled Islanding. *Energies* **2018**, *11*, 143. [CrossRef]
104. Liu, Y.; Sun, J.; Chen, Q.; Xia, M. Distribution Network Topology Error Identification Method Based on D-PMU and Branch State Function. In Proceedings of the 2019 IEEE Innovative Smart Grid Technologies—Asia (ISGT Asia), Chengdu, China, 21–24 May 2019; pp. 821–826. [CrossRef]
105. Meng, Y.; Yu, Z.; Lu, N.; Shi, D. Time Series Classification for Locating Forced Oscillation Sources. *IEEE Trans. Smart Grid* **2021**, *12*, 1712–1721. [CrossRef]
106. Baltas, G.; Lai, N.-B.; Tarraso, A.; Marin, L.; Blaabjerg, F.; Rodriguez, P. AI-Based Damping of Electromechanical Oscillations by Using Grid-Connected Converter. *Front. Energy Res.* **2021**, *9*, 598436. [CrossRef]
107. Mukherjee, S.; Chakrabortty, A.; Bai, H.; Darvishi, A.; Fardanesh, B. Scalable Designs for Reinforcement Learning-Based Wide-Area Damping Control. *IEEE Trans. Smart Grid* **2021**, *12*, 2389–2401. [CrossRef]
108. Abdulrahman, I.; Radman, G. Wide-Area-Based Adaptive Neuro-Fuzzy SVC Controller for Damping Interarea Oscillations. *Can. J. Electr. Comput. Eng.* **2018**, *41*, 133–144. [CrossRef]
109. Mejia-Ruiz, G.E.; Cárdenas-Javier, R.; Paternina MR, A.; Rodríguez-Rodríguez, J.R.; Ramirez, J.M.; Zamora-Mendez, A. Coordinated Optimal Volt/Var Control for Distribution Networks via D-PMUs and EV Chargers by Exploiting the Eigensystem Realization. *IEEE Trans. Smart Grid* **2021**, *12*, 2425–2438. [CrossRef]
110. Liu, H.; Su, J.; Yang, Y.; Qin, Z.; Li, C. Compatible Decentralized Control of AVR and PSS for Improving Power System Stability. *IEEE Syst. J.* **2021**, *15*, 2410–2419. [CrossRef]
111. Alkhalaf, S. Modeling the Automatic Voltage Regulator (AVR) Using Artificial Neural Network. In Proceedings of the 2019 International Conference on Innovative Trends in Computer Engineering (ITCE), Aswan, Egypt, 2–4 February 2019; pp. 570–575. [CrossRef]
112. Bliznyuk, D.; Berdin, A.; Kovalenko, P.; Dekhtiar, S.; Gerasimov, A. Defining the damping properties of synchronous generator using disturbance measurements. In Proceedings of the 2017 9th International Conference on Information Technology and Electrical Engineering (ICITEE), Phuket, Thailand, 12–13 October 2017; pp. 1–5. [CrossRef]
113. Pierrou, G.; Wang, X. An Online Network Model-Free Wide-Area Voltage Control Method Using PMUs. *IEEE Trans. Power Syst.* **2021**, *36*, 4672–4682. [CrossRef]
114. Huang, Q.; Huang, R.; Hao, W.; Tan, J.; Fan, R.; Huang, Z. Adaptive Power System Emergency Control Using Deep Reinforcement Learning. *IEEE Trans. Smart Grid* **2020**, *11*, 1171–1182. [CrossRef]
115. Moiseichenkov, A.N.; Senyuk, M.D.; Kovalenko, P.Y.; Dmitrieva, A.A. The Technique of Calculating a Steam Turbine Power for Characterization of The Turbine Fast Valving. In Proceedings of the 2021 International Conference on Electrotechnical Complexes and Systems (ICOECS), Ufa, Russia, 16–18 November 2021; pp. 79–82. [CrossRef]
116. Senyuk, M.; Safaraliev, M.; Gulakhmadov, A.; Ahyoev, J. Application of the Conditional Optimization Method for the Synthesis of the Law of Emergency Control of a Synchronous Generator Steam Turbine Operating in a Complex-Closed Configuration Power System. *Mathematics* **2022**, *10*, 3979. [CrossRef]
117. Senyuk, M.D.; Moiseichenkov, A.N.; Kovalenko, P.Y.; Dmitrieva, A.A. Adaptive Algorithm for Steam Turbine Fast Valving Based on the Equal Area Criterion and Synchrophasor Measurements. In Proceedings of the 2021 International Conference on Electrotechnical Complexes and Systems (ICOECS), Ufa, Russia, 16–18 November 2021; pp. 68–73. [CrossRef]
118. Beryozkina, S.; Senyuk, M.; Berdin, A.; Dmitrieva, A.; Dmitriev, S.; Erokhin, P. The Accelerate Estimation Method of Power System Parameters in Static and Dynamic Processes. *IEEE Access* **2022**, *10*, 61522–61529. [CrossRef]
119. Pavlovski, M.; Alqudah, M.; Dokic, T.; Hai, A.A.; Kezunovic, M.; Obradovic, Z. Hierarchical Convolutional Neural Networks for Event Classification on PMU Measurements. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 1–13. [CrossRef]
120. Hai, A.A.; Dokic, T.; Pavlovski, M.; Mohamed, T.; Saranovic, D.; Alqudah, M.; Kezunovic, M.; Obradovic, Z. Transfer Learning for Event Detection from PMU Measurements with Scarce Labels. *IEEE Access* **2021**, *9*, 127420–127432. [CrossRef]

121. Shahsavari, A.; Farajollahi, M.; Stewart, E.M.; Cortez, E.; Mohsenian-Rad, H. Situational Awareness in Distribution Grid Using Micro-PMU Data: A Machine Learning Approach. *IEEE Trans. Smart Grid* **2019**, *10*, 6167–6177. [CrossRef]
122. Shi, J.; Foggo, B.; Yu, N. Power System Event Identification Based on Deep Neural Network with Information Loading. *IEEE Trans. Power Syst.* **2021**, *36*, 5622–5632. [CrossRef]
123. Duan, N.; Stewart, E.M. Frequency Event Categorization in Power Distribution Systems Using Micro PMU Measurements. *IEEE Trans. Smart Grid* **2020**, *11*, 3043–3053. [CrossRef]
124. Grando, F.L.; Lazzaretti, A.E.; Moreto, M.; Lopes, H.S. Fault Classification in Power Distribution Systems using PMU Data and Machine Learning. In Proceedings of the 20th International Conference on Intelligent System Application to Power Systems (ISAP), Istanbul, Turkey, 10–14 December 2019; pp. 1–6. [CrossRef]
125. Ahmed, A.; Sajan, K.S.; Srivastava, A.; Wu, Y. Anomaly Detection, Localization and Classification Using Drifting Synchrophasor Data Streams. *IEEE Trans. Smart Grid.* **2021**, *12*, 3570–3580. [CrossRef]
126. Shrivastava, D.; Siddiqui, S.; Verma, K. A new synchronized data-driven-based comprehensive approach to enhance real-time situational awareness of power system. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12887. [CrossRef]
127. Huang, T.; Freris, N.M.; Kumar, P.R.; Xie, L. A Synchrophasor Data-Driven Method for Forced Oscillation Localization Under Resonance Conditions. *IEEE Trans. Power Syst.* **2020**, *35*, 3927–3939. [CrossRef]
128. Papadopoulos, P.N.; Papadopoulos, T.A.; Chrysochos, A.I.; Milanović, J.V. Measurement Based Method for Online Characterization of Generator Dynamic Behaviour in Systems with Renewable Generation. *IEEE Trans. Power Syst.* **2018**, *33*, 6466–6475. [CrossRef]
129. Kim, D.-I.; Wang, L.; Shin, Y.-J. Data Driven Method for Event Classification via Regional Segmentation of Power Systems. *IEEE Access* **2020**, *8*, 48195–48204. [CrossRef]
130. Li, H.; Ma, Z.; Weng, Y. A Transfer Learning Framework for Power System Event Identification. *IEEE Trans. Power Syst.* **2022**, *37*, 4424–4435. [CrossRef]
131. Nuqui, R.F.; Phadke, A.G. Phasor measurement unit placement techniques for complete and incomplete observability. *IEEE Trans. Power Del.* **2005**, *20*, 2381–2388. [CrossRef]
132. Singh, B.; Pal, C.; Vinter, R.B. Measurement placement in distribution system state estimation. *IEEE Trans. Power Syst.* **2009**, *24*, 668–675. [CrossRef]
133. Peng, Y.; Wu, Z.; Fang, C.; Zheng, S.; Zhao, J. Optimal PMU Placement in Distribution Networks for Improving State Estimation Accuracy and Fault Observability. In Proceedings of the 2021 IEEE Sustainable Power and Energy Conference (iSPEC), Nanjing, China, 23–25 December 2021; pp. 1413–1418. [CrossRef]
134. Khalafi, Z.; Dehghani, M.; Goel, L.; Li, W. Observability reliability evaluation in power systems considering data uncertainty. In Proceedings of the 2015 IEEE Eindhoven PowerTech, Eindhoven, The Netherlands, 29 June–2 July 2015; pp. 1–5. [CrossRef]
135. Esmaili, M.; Ghamsari-Yazdel, M. Voltage Stability-Constrained Optimal Simultaneous Placement of PMUs and Channels Enhancing Measurement Reliability and Redundancy. *IEEE Power Energy Technol. Syst. J.* **2017**, *4*, 32–39. [CrossRef]
136. Dua, D.; Dambhare, S.; Gajbhiye, R.K.; Soman, S.A. Optimal Multistage Scheduling of PMU Placement: An ILP Approach. *IEEE Trans. Power Deliv.* **2008**, *23*, 1812–1820. [CrossRef]
137. Rakpenthai, C.; Premrudeepreechacharn, S.; Uatrongjit, S.; Watson, N.R. An Optimal PMU Placement Method Against Measurement Loss and Branch Outage. *IEEE Trans. Power Deliv.* **2007**, *22*, 101–107. [CrossRef]
138. Devendran, V.S.; Jasni, J.; Radzi, M.A.M.; Azis, N. Optimal Placement of PMU for Complete Observability of Power System Considering Zero Injection and Islanding Condition. In Proceedings of the 2020 IEEE International Conference on Power and Energy (PECon), Penang, Malaysia, 7–8 December 2020; pp. 107–112. [CrossRef]
139. Manda, S.; Balakrishna, K.; Sriharibabu, A. Linear programming method to find the minimal placements of phasor measuring units for power system state estimation. In Proceedings of the 2017 International Conference on Power and Embedded Drive Control (ICPEDC), Chennai, India, 16–18 March 2017; pp. 360–364. [CrossRef]
140. Aminifar, F.; Lucas, C.; Khodaei, A.; Fotuhi-Firuzabad, M. Optimal Placement of Phasor Measurement Units Using Immunity Genetic Algorithm. *IEEE Trans. Power Deliv.* **2009**, *24*, 1014–1020. [CrossRef]
141. Dixit, A.; Jain, S.K. Genetic algorithm based optimal placement of phasor measurement units for harmonic source identification. In Proceedings of the 2016 7th India International Conference on Power Electronics (IICPE), Patiala, India, 17–19 November 2016; pp. 1–6. [CrossRef]
142. Geramian, S.S.; Abyane, H.A.; Mazlumi, K. Determination of optimal PMU placement for fault location using genetic algorithm. In Proceedings of the 2008 13th International Conference on Harmonics and Quality of Power, Wollongong, NSW, Australia, 28 September–1 October 2008; pp. 1–5. [CrossRef]
143. Tarif, T.; Ladjici, A.A.; Chabane, Y. Optimal PMU placement for small-signal stability assessment using Genetic algorithm. In Proceedings of the 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, Algeria, 28–31 October 2018; pp. 1–6. [CrossRef]
144. Rammal, Z.A.; Daher, N.A.; Kanaan, H.; Mougharbel, I.; Saad, M. Optimal PMU placement for reverse power flow detection. In Proceedings of the 2018 4th International Conference on Renewable Energies for Developing Countries (REDEC), Beirut, Lebanon, 1–2 November 2018; pp. 1–5. [CrossRef]
145. Dalawai, P.P.; Abhyankar, A.R. Placement of PMUs for complete and incomplete observability using search technique. In Proceedings of the 2013 Annual IEEE India Conference (INDICON), Mumbai, India, 13–15 December 2013; pp. 1–5. [CrossRef]

146. Babu, R.; Bhattacharyya, B. Optimal placement of phasor measurement unit using binary particle swarm optimization in connected power network. In Proceedings of the 2015 IEEE UP Section Conference on Electrical Computer and Electronics (UPCON), Allahabad, India, 4–6 December 2015; pp. 1–5. [CrossRef]
147. Mishra, S.K.; Swain, K.B.; Cherukuri, M. Optimal Placement of Phasor Measurement Unit Using Quantum Particle Swarm Optimization. In Proceedings of the 2021 1st International Conference on Power Electronics and Energy (ICPEE), Bhubaneswar, India, 2–3 January 2021; pp. 1–4. [CrossRef]
148. Patel, M.; Talati, S. Optimal PMU Placement by Improved Cuckoo & PSO Method. In Proceedings of the 2021 International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), Bhilai, India, 19–20 February 2021; pp. 1–6. [CrossRef]
149. Tawfik, A.S.; Abdallah, E.N.; Youssef, K.H. Optimal placement of phasor measurement units using binary bat algorithm. In Proceedings of the 2017 Nineteenth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 19–21 December 2017; pp. 559–564. [CrossRef]
150. Tawfik, N.M.; El-Amary, N.H.; Nasrat, L. Phasor Measurement Unit Optimal Allocation Utilizing Discrete Water Cycle Optimization. In Proceedings of the 2023 5th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Moscow, Russia, 16–18 March 2023; pp. 1–6. [CrossRef]
151. Jaiswal, V.; Thakur, S.S.; Mishra, B. Optimal placement of PMUs using Greedy Algorithm and state estimation. In Proceedings of the 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, India, 4–6 July 2016; pp. 1–5. [CrossRef]
152. Rigatos, G.; Zervos, N.; Siano, P.; Wira, P.; Abbaszadeh, M. Nonlinear Optimal Control for Steam-Turbine Power Generation. In Proceedings of the2018 5th International Symposium on Environment-Friendly Energies and Applications (EFEA), Rome, Italy, 24–26 September 2018; pp. 1–7. [CrossRef]
153. Senyuk, M.; Safaraliev, M.; Kamalov, F.; Sulieman, H. Power System Transient Stability Assessment Based on Machine Learning Algorithms and Grid Topology. *Mathematics* **2023**, *11*, 525. [CrossRef]
154. Senyuk, M.; Rajab, K.; Safaraliev, M.; Kamalov, F. Evaluation of the Fast Synchrophasors Estimation Algorithm Based on Physical Signals. *Mathematics* **2023**, *11*, 256. [CrossRef]
155. Senyuk, M.; Beryozkina, S.; Gubin, P.; Dmitrieva, A.; Kamalov, F.; Safaraliev, M.; Zicmane, I. Fast Algorithms for Estimating the Disturbance Inception Time in Power Systems Based on Time Series of Instantaneous Values of Current and Voltage with a High Sampling Rate. *Mathematics* **2022**, *10*, 3949. [CrossRef]
156. *IEEE Std C37.242-2021*; IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control. Revision of IEEE Std C37.242-2013; IEEE Standards Association: Piscataway, NJ, USA, 2021; pp. 1–98. [CrossRef]