Phasor Measurement Units for Modern Power Systems

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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.

phasor measurement unit | relay protection | fault | digital substation

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 researchers 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][8][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][11][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 researchers 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.

2. 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 [13]. 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. Researchers 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 [14], including those aimed at improving the observability and minimizing the number of critical measurements [15]. In [16][17], the use of PMUs is considered for a robust SE based on the method of smallest modules. In [18], the SE of PMUs is solved on the basis of the method of control equations. In [19][20], 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.

2.1. Classical WLSM SE, Expanded by PMU Data

In [21][22], 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.

2.2. 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.

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

With a two-level SE based on the framework of the PMU [23], 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.

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

In [24][25] 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 [24] 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.

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

In [26][27], 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 researchers 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 [28]. 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.

2.6. 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 [29]. 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. 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.

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

According to the requirements of the existing regulatory and technical documentation [30], 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 researchers 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.

3.2. 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 [31]. 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 [32]. 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 [33], 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 1**.

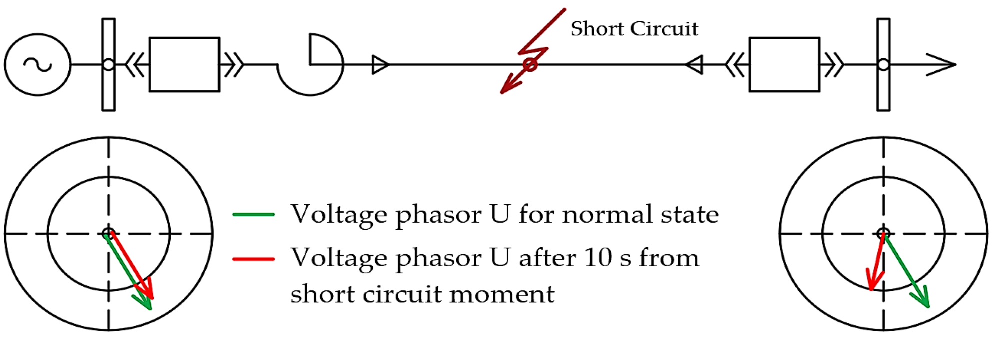

Figure 1. Change of voltage vectors in case of a short circuit on the line.

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 [34][35][36][37], 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 [38], 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 2**.

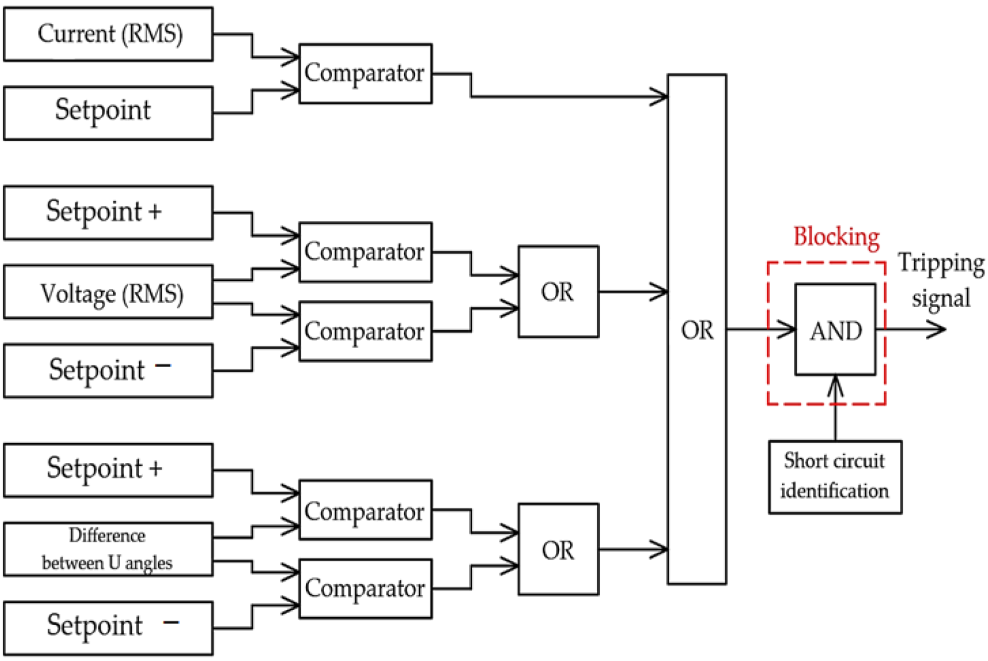

Figure 2. Block diagram of the use of voltage vectors to implement the current protection blocking function.

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 [39] 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 [40]. 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 [41] 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 [42] and third [43] zones, as well as the correction in response time of the stages intended for long-range redundancy in the direction of its reduction [35]. **Figure 3** shows the response characteristics with the degree of longitudinal compensation of the line equal to 20% and 60%.

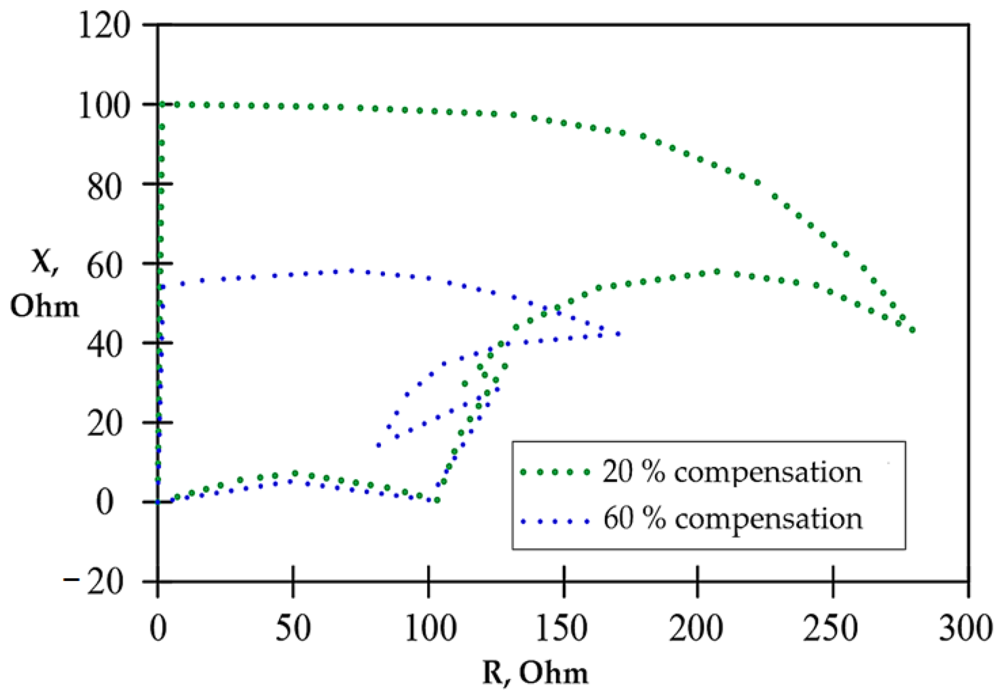

Figure 3. Characteristic of line resistance change.

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 [44][45].

It is proposed to ensure the correct operation of the third stages of remote protection during circuit-mode changes in the network in [46] 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 [47], 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 [47], as well as in other publications [48][49], vector measurements are used in the algorithms for determining the equivalent resistance of a system in on-line mode. **Figure 4** shows the change in the shape of the characteristic when the resistance of the equivalent of the system changes.

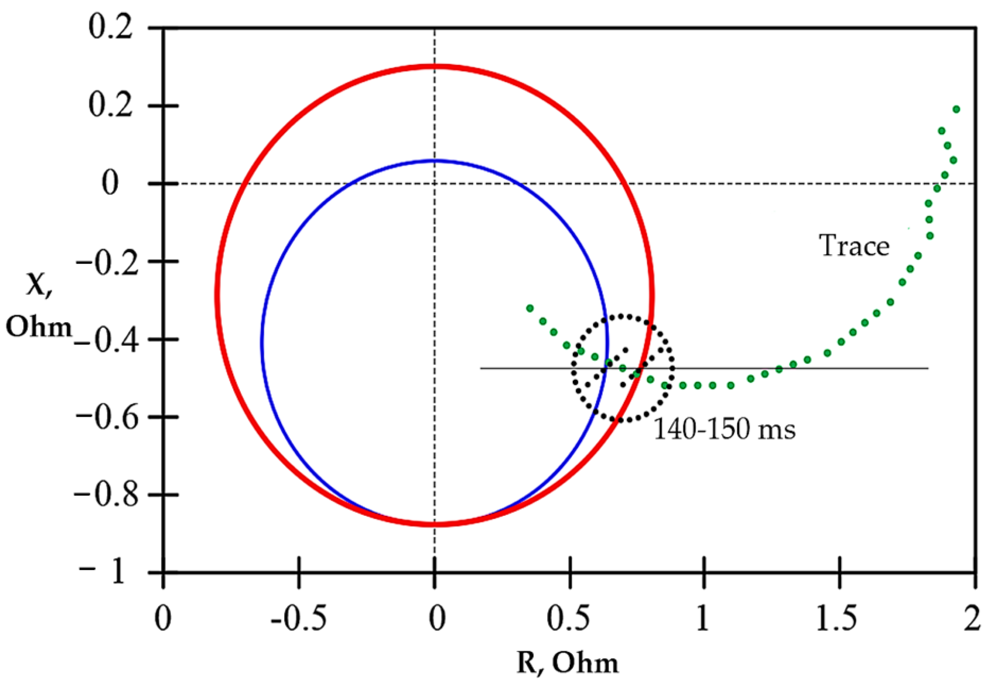

Figure 4. Estimation of damage detection time.

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 [50]. 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 [51]. 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 [52] 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.

3.3. 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 [53] 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 [54]. 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.

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.
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.
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.
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.

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.
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.
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.
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.
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.
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.
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.
13. 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.
14. 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.
15. 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.

16. Göl, M.; Abur, A. LAV Based Robust State Estimation for Systems Measured by PMUs. IEEE Trans. Smart Grid 2014, 5, 1808–1814.
17. Göl, M.; Abur, A. A Hybrid State Estimator for Systems with Limited Number of PMUs. IEEE Trans. Power Syst. 2015, 30, 1511–1517.
18. 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.
19. 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.
20. 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.
21. 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.
22. 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.
23. 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.
24. 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.
25. 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.
26. 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.
27. 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.
28. Joshi, P.M.; Verma, H. Synchrophasor measurement applications and optimal PMU placement: A review. Electr. Power Syst. Res. 2021, 199, 107428.

29. 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.
30. 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.
31. 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.
32. 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.
33. Leibovich, P.; Issouribehere, F.; Barbero, J. Design and Implementation of a low-cost PMU: Validation by tests and perfor-mance 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.
34. 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.
35. 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.
36. 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.
37. 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.
38. 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.
39. 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.

40. 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.

41. 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.

42. 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.

43. 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.

44. Naeini, E.; Vaseghi, B.; Mahdavian, M. Modified Transmission Line Protection Scheme in the Presence of SCC. J. Electr. Eng. Technol. 2017, 12, 533–540.

45. 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.

46. 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.

47. 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.

48. 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.

49. 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.

50. 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.

51. Skok, S.; Frlan, K.; Ugarkovic, K. Detection and Protection of Distributed Generation from Island Operation by Using PMUs. Energy Procedia 2017, 141, 438–442.

52. 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.
53. 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.
54. 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.