 https://doi.org/10.1051/e3sconf/202346101035

# Application of WAMPAC principles in distribution networks

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**Abstract.** The paper examines the dissemination of principles for constructing WAMPAC systems in medium voltage networks. The authors provide the prerequisites for the use of WAMPAC in distribution networks and show the advantages of such systems over traditional ones. The first part of the paper considers directions for the development of monitoring, protection and automation systems in the distribution network. The second part is devoted to the localization of ground faults based on phasor measurement technology. The paper also presents the results of mathematical modeling and data on the experience of applying WAMPAC principles in 10 kV cable networks.

## 1 Introduction

The term WAMPAC (Wide Area Monitoring, Protection, Automation, and Control) appeared recently in the scientific community [1]. It gives a general designation for distributed monitoring, protection, automation and control systems implemented using synchronized phasor measurement (SPM) technology and PMUs. Currently, there are many areas of SPM application in the electric power industry to improve the reliability, stability and efficiency of power system management [2-3].

The initial concept of WAMPAC systems assumed strict compliance with the developed standard for PMU [4]. The authors emphasize that this approach limits both the development of the WAMPAC systems themselves and the areas of synchrophasor technology application.

Currently, there are several new approaches for WAMPAC systems, taking into account the development of their architecture and integration with other existing systems, in particular, SCADA [5]. The authors consider the issue of organizing several levels of WAMPAC management and their relationship with each other.

The authors suggest that the development of new technologies allows consider the WAMPAC application in both high and medium voltage networks. Synchrophasor technology has many promising areas for distribution networks, so the task of introducing WAMPAC is relevant here. In addition, there are other reasons for using WAMPAC in such networks (complex structure, distributed generation, non-linear load of consumers) [6].

Previously, the authors outlined general approaches to the implementation of wide area protection, monitoring, automation and control systems in medium voltage networks [7]. This paper is a continuation of research in the field of SPM application for distribution networks.

The paper has three main sections. Section 2 examines general issues of applying WAMPAC principles in medium voltage networks; the authors present relevant directions for automating such networks [8-10]. Section 3 describes a fault localization system based on equivalent harmonic synchrophasors (EHS). Section 4 considers the experience of applying WAMPAC principles in existing electrical networks [11].

## 2 WAMPAC applications

The reliability and quality of power supply to consumers of urban, rural and industrial distribution networks directly depends on the level of their automation. The challenges of developing medium voltage networks require rational and effective solutions based on the use of modern intelligent devices and technologies.

The following studies present the benefits of WAMPAC principles for power systems [2-3]. However, the authors limit the WAMPAC application to high voltage networks. At the same time, synchrophasor technology has prospects for use in medium voltage networks. We can solve this problem using new types of synchrophasor devices [7].

One of the main advantages of WAMPAC systems is their multi-level structure, which allows the implementation of central and several local levels of distribution network management.

In Fig. 1, the authors show the structure of the multi-level WAMPAC system in the distribution network.

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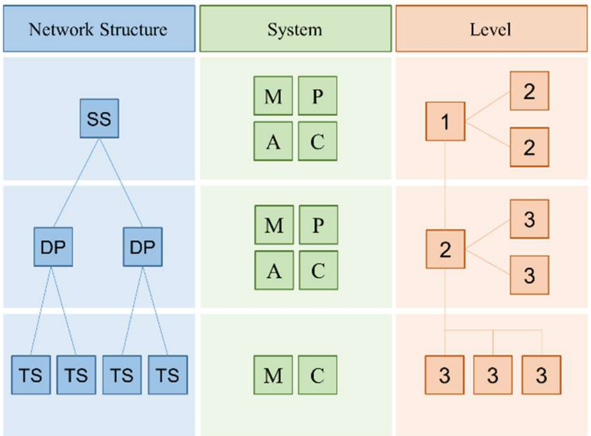
https://doi.org/10.1051/e3sconf/202346101035




SS – Substation, DP – Distribution Point, TS – Transformer Substation 6(10)/0.4 kV, M – Monitoring, P – Protection, A – Automation, C – Control

**Fig. 1.** WAMPAC principles for distribution network

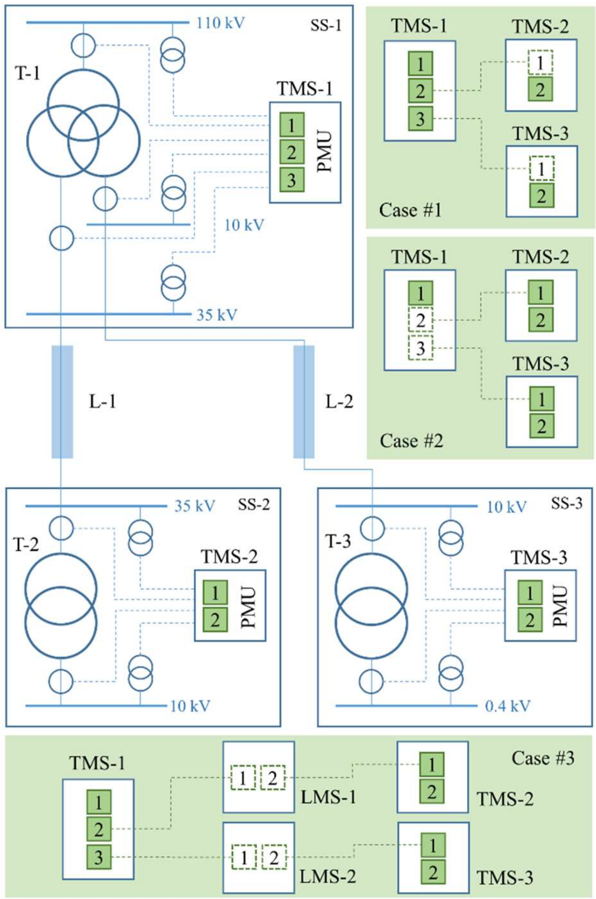
Fig. 1 has the following concept. Synchrophasor technology is an important part of WAMPAC, so based on it we can implement a centralized protection system for a substation or distribution point [8]. SPM technology opens up opportunities for the application of the differential principle of protection of substation buses and power transformer [9] and the distance principle for line protection [12-13]. The WAMPAC principles make it possible to ensure high performance protection in a centralized mode and maintain its reliability in a local mode when the communication network is partially or completely degraded.

We can apply a similar approach to WAMPAC in other distribution network systems. For example, a FLISR system (Fault Location, Isolation and Supply Restoration) that includes a fault localization subsystem may have several local control levels (transformer substation level) and a central level (substation/distribution point level) [11]. The presence of local levels allows for a phased modernization of the network, reducing the requirements for the technical characteristics of the system, in particular, for data transmission channels.

Let us consider an example that shows how the WAMPAC principles and synchrophasor technology make it possible to implement equipment state monitoring and network monitoring while reducing capital costs for the monitoring system (Fig. 2).

SPM provides measurements for transformer monitoring systems [9]. Such systems include monitoring of transformer electrical parameters (current and voltage synchrophasors, equivalent circuit parameters, power losses), which is an effective solution for distribution networks, since in many cases there are no other monitoring systems.

Fig. 2 shows two cases (1-2), which explain how, based on PMU, we organize monitoring of transformers at adjacent substations. Here, using the existing principles of PMU placement [14] and additional calculation of synchrophasors at an adjacent substation, we can implement monitoring of those transformers for which part of the synchrophasor measurements is missing.




TMS – Transformer Monitoring System, LMS – Line Monitoring System

**Fig. 2.** Network and equipment monitoring

Case #3 (Fig. 2) also confirms that we can use PMU data to monitor other elements of the system, for example, to monitor power lines (L-1 and L-2). The authors suggest that a promising and effective solution is the integration of monitoring system functions in relay protection devices based on synchrophasor technology.

The WAMPAC principles are promising for the development of automation systems for networks with distributed generation and renewable energy sources [6]. Important tasks here are the advanced microgrid applications and operation, improved load shedding schemes, advanced distribution automation, real-time distribution system operation [15].

One of the most important and complex tasks for the automation of medium voltage distribution networks is fault localization, in particular the localization of single-phase ground faults (SGF). Let us consider in more detail the application of WAMPAC principles for the implementation of SGF localization system.

## 3 Fault localization

The authors presented methods for localizing short circuits and single-phase ground faults using synchrophasor technology in [11]. However, our work in this area is still ongoing, and we can present new research results in this paper.

Currently, there are several main methods for localizing SGF in medium voltage networks [16-17]. An urgent task is to develop new methods for networks with partial or full compensation of ground fault current. In this regard, the authors propose the use of equivalent zero sequence current and voltage synchrophasors [18].

A network with an isolated neutral makes it possible to implement maximum current and current directional SGF protection [17]. This is because in such a network the capacitive current of undamaged phases during a ground fault is directed to the fault location, so we can select the settings according to the theoretical values of the capacitive currents of the feeders. We can express this principle in zero sequence current synchrophasors:

$$\dot{I}_{0i}(t) = \dot{I}_{Ci}(t)\,, \qquad (1)$$

$$\dot{I}_{0k}(t) = -\sum_{i=1}^{N} \dot{I}_{Ci}(t) + \dot{I}_{Ck}(t)\,, \qquad (2)$$

where $i-$ number of undamaged network feeder, $k$ $-$feeder with ground fault, $\dot{I}_{0i}(t)$ $-$ zero sequence current synchrophasor, $\dot{I}_{Ci}(t)-$ capacitive current.

Expressions (1) and (2) are valid for fundamental frequency synchrophasors and for the steady state SGF mode. The minus sign in expression (2) indicates that the currents and should have opposite directions in a network with an isolated neutral.

We can represent dependence (1) and (2) through an estimation of the feeder capacity:

$$C_i(t) = C_i\,, \qquad (3)$$

$$C_k(t) = \sum_{i=1}^{N} C_i - C_k\,. \qquad (4)$$

Expressions (1) - (4) are valid for a network with an isolated neutral and do not correspond to a network with compensation of the SGF current. In this case, we can use the active or harmonic components of the zero sequence current to identify the faulty feeder [17]. However, a network with full SGF current compensation allows only transient measurements to be used [16].

Measuring instantaneous values of zero sequence current and voltage in the transient SGF mode has certain difficulties due to the pulsed nature of such a process. In addition, methods that use zero sequence current harmonics to identify a faulty feeder require the development of specific harmonic filters. At the same time, there is no a priori data on the composition and level of harmonics in the zero sequence current, so the selection of harmonic filters is a complex task. In this regard, the authors propose the use of equivalent synchrophasors of zero sequence current and voltage harmonics (EHS) to improve algorithms for localizing faults in a network with a compensated neutral.

We previously reviewed the terms and theory of equivalent synchrophasors in [18]. Therefore, in this paper we use the following notations: $\dot{I}_{0e}(t)$, $\dot{U}_{0e}(t)$ - equivalent synchrophasors, including harmonic and fundamental frequency components, $\dot{I}_{0h}(t)$, $\dot{U}_{0h}(t)$ - equivalent harmonic synchrophasors (EHS).

Based on the provisions of the theory of electrical circuits, we can argue that in the transient SGF mode in a network with a compensated neutral, the arc suppression reactor does not compensate for the capacitive SGF current due to the significant inertia of the inductor. In this regard, we propose measuring equivalent synchrophasors to create a system for localizing SGF based on the principle of measuring transient electrical quantities. In the simplest case, we can use the estimation of fundamental frequency synchrophasors for this purpose.

Another direction for localizing faults in such networks involves measuring harmonics in zero sequence current and voltage. There are studies that confirm that distribution networks have significant harmonic components in the zero sequence circuit [17]. As we noted earlier, methods that involve measuring harmonics require the development of special filters. We propose the use of equivalent harmonic synchrophasors as the most rational option for solving this problem.

Both principles (measurement of equivalent synchrophasors of the transient SGF and measurement of equivalent harmonic synchrophasors) make it possible to implement a local and central control level of SGF localization system. This is in accordance with the WAMPAC principles in the distribution network. The local mode assumes that we can estimate the capacitances of individual feeders and determine the direction to the SGF location. The central control level allows determining a specific damaged section of the network.

The authors also propose another concept, which suggests that we can combine the considered methods of SGF localization to improve the efficiency of the system as a whole. In addition, we continue research to develop other methods for localizing SGF, in particular based on the transformation of the line differential equation.

Existing methods based on the transformation of the line differential equation use instantaneous values of zero sequence currents and voltages. The line capacity estimate in this case has the following expression:

$$3i_0(t) \approx C_0 \frac{du_0(t)}{dt}\,. \qquad (5)$$

The authors emphasize that the use of instantaneous values of currents and voltages when solving the problem under consideration can lead to significant difficulties in implementing the SGF localization algorithm, since in the transient SGF mode the derivative of the zero sequence current and voltage can take on large absolute values. We consider that a much more effective approach is to estimate the capacitance from the integral values of the synchrophasors:

$$C_0(t) \approx \frac{3\dot{I}_0(t)}{j\omega_0 \dot{U}_0(t) + \dot{U}_0'(t)}\,, \qquad (6)$$

where $\dot{U}_0'(t) = \dfrac{d\dot{U}_0(t)}{dt}$.

 https://doi.org/10.1051/e3sconf/202346101035

The authors obtained a more accurate estimate of the capacitance taking into account the conductivity of the network and in the presence of measurements of the current of the arc suppression reactor:

$$C_0(t) \approx \frac{1}{3} \frac{j\omega_0 \dot{I}_0(t) + \dot{I}_0'(t) + L_k^{-1}\dot{U}_0(t)}{\underline{a}_0 \dot{U}_0(t) - \underline{a}_1 \dot{U}_0'(t) - \dot{U}_0''(t)}, \qquad (7)$$

where $\dot{U}_0''(t) = \frac{d^2\dot{U}_0(t)}{dt^2}$, $\dot{I}_0'(t) = \frac{d\dot{I}_0(t)}{dt}$, $k = \frac{G_{0\mu}}{C_{0\mu}}$, $\underline{a}_1 = 2j\omega_0 + k$, $\underline{a}_0 = \omega_0^2 - j\omega_0 k$, $G_{0\mu}$ − feeder conductivity (per km), $C_{0\mu}$ − feeder capacity (per km), $L_k$ − reactor inductance.

Thus, WAMPAC and synchrophasor technology make it possible to implement several new algorithms for localizing SGF in the distribution network.

## 4 SGF modeling

Let us consider an example of modeling the proposed algorithms for localizing SGF in Simulink. Fig. 3 shows a diagram of a network model with a compensated neutral. The network has two segments (damaged 1 and undamaged 2). The capacity of the undamaged segment 1 of the network is greater than the capacity of the damaged section 2 (in a ratio of 2:1). This makes it possible to compare the ratio of zero sequence currents across network segments in transient and steady state SGF modes.

Fig. 4 shows a comparison of equivalent synchrophasors and EHS of the zero-sequence current of a damaged and undamaged network segment. Fig. 5 shows the estimation of the segment's capacity using expression (6).

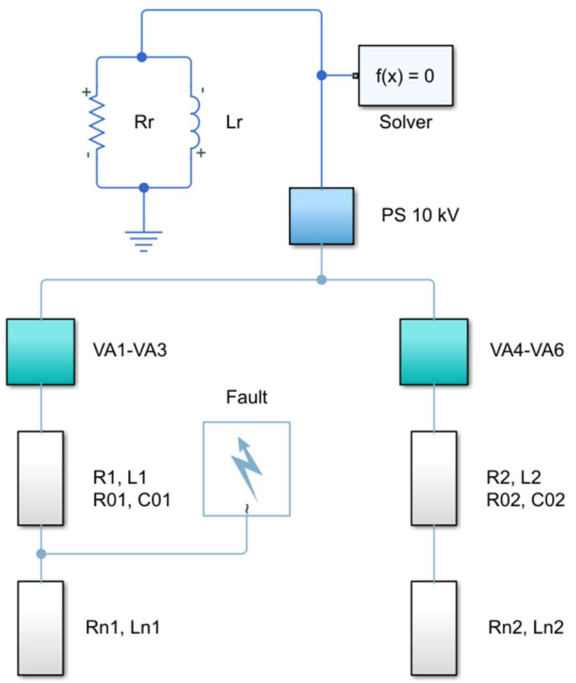



**Fig. 3.** Simulink test model

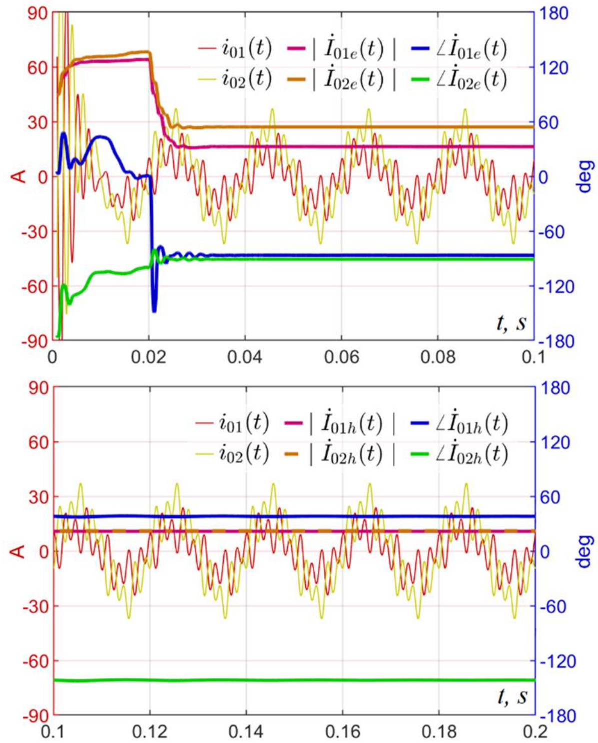



**Fig. 4.** Comparison of equivalent synchrophasors

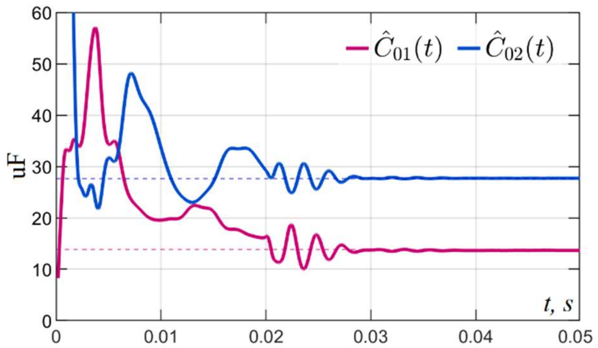



**Fig. 5.** Estimating the capacity of model segments

Fig. 4 confirms that the use of equivalent current synchrophasors in the transient mode (0-20 ms) and EHS in the steady state (> 20 ms) makes it possible to increase the efficiency of SGF localization algorithms by comparing the magnitude and phase of the corresponding synchrophasors of the damaged and undamaged area.

Fig. 5 confirms the effectiveness of expression (6) for estimating the capacity of network segments during SGF.

## 5 Practical experience

Currently, we have implemented several monitoring and control systems in the distribution network based on WAMPAC principles [11]. First, we would like to note the positive experience of using SPM for SGF localization in 10 kV cable networks. For this purpose, we have developed a special device with SPM support (ENLZ). The localization system operates at several operating facilities in Arkhangelsk and Cherepovets (Russia). The system measures and uses fundamental frequency zero sequence current and voltage synchrophasors. We obtained a cost-effective solution by reducing the requirements for measurement accuracy for the ENLZ device compared to PMU [4], as well as using split-core zero sequence current transformers.

Secondly, we can note the prospects for implementing monitoring systems for power transformers based on measurements of voltage and current synchrophasors. Currently, such a system is in pilot operation at two substations in Arkhangelsk (Russia) [11]. Important advantages of the system include the ability to evaluate the parameters of the equivalent circuit and power losses in the transformer in its operating mode.

## 6 Conclusion

The paper considers that the WAMPAC principles have promising applications in medium voltage networks. The authors show the advantages of a multi-level structure of automation, monitoring, protection and control systems. Using the example of an SGF localization system, we showed the effectiveness of using equivalent synchrophasors and EHS of zero sequence current and voltage. The paper presents the results of research using mathematical models and data from pilot industrial operation.

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