The use of symmetrical components in electrical protection

Ciontea, Catalin-Iosif

Published in:
Proceedings of 2019 72nd Conference for Protective Relay Engineers (CPRE)

DOI (link to publication from Publisher):
10.1109/CPRE.2019.8765870

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Ciontea, C-I. (2019). The use of symmetrical components in electrical protection. In *Proceedings of 2019 72nd Conference for Protective Relay Engineers (CPRE)* [8765870] IEEE Press. https://doi.org/10.1109/CPRE.2019.8765870

The Use of Symmetrical Components in Electrical Protection

Catalin Iosif Ciontea
Department of Research and Development
DEIF A/S
Skive, Denmark
cic@deif.com

***Abstract*—in some situations, the symmetrical components of voltage and current are more sensitive to electric faults compared to their phase-domain counterparts. For this reason, several protection relays operate on symmetrical components and many protection engineers continue to develop protection algorithms that rely on these quantities. This paper reviews the literature on the use of symmetrical components in electrical protection and sorts it in categories covering line protection, generator/motor protection, transformer protection and protection of distribution networks and microgrids. The review shows that symmetrical components are used by over-current/-voltage elements, distance relaying, directional algorithms, differential schemes, adaptive protection and protection algorithms based on relationships of symmetrical components. This paper also presents, in short, the theoretical background of symmetrical components and their derivation from the phase-domain quantities.**

Keywords—electrical faults, protection relaying, symmetrical components, positive-sequence, negative-sequence, zero-sequence, unbalanced system conditions

I. INTRODUCTION (*HEADING 1*)

The method of symmetrical components was introduced by Canadian engineer Charles LeGeyt Fortescue at the 1918 edition of the Annual Convention of the American Institute of Electrical Engineers [1], [2]. Subsequently, it has become an essential tool in engineering, simplifying the analysis of multi-phase electrical circuits operating under unbalanced conditions. The method of symmetrical components is used, for example, to calculate the short-circuit currents in power system planning and in protection studies. In addition, the operation of some protection systems is based on Fortescue's method [3].

With the advancement of electronic and numerical relays, it is possible to implement more complex protection algorithms that use the method of symmetrical components. Several such algorithms have been proposed over the years for protection in many applications, including high voltage power systems, wind farms, distribution networks, microgrids and others. Due to the relatively large number of technical papers discussing protection algorithms, protection schemes and protection techniques based on the method of symmetrical components, the author considers it appropriate to carry out a thorough review of the literature on this subject. Therefore, this paper reviews the most recent and relevant technical publications regarding the use of symmetrical components in the protection relaying and sorts them according to the application to which they are addressed. Accordingly, the literature is sorted into line protection, transformer protection, protection of electrical machines, and protection of distribution networks and microgrids.

The rest of this paper is structured as follows. In section II, the fundamentals of the method of symmetrical components are introduced. In Section III, the review of the selected technical papers is presented. Section IV concludes this paper with some considerations regarding the future of symmetrical components in electrical protection.

II. METHOD OF SYMMETRICAL COMPONENTS

The method of symmetrical components has the foundation on Fortescue's theorem, which states that an unbalanced set of N related phasors can be expressed when N is a prime number as a linear combination of N symmetrical sets of N phasors [2]. The resulting sets of phasors represent the symmetrical or sequence components of the initial set of phasors. When N is not prime, some of symmetrical sets of phasors degenerate into rehearsals of the symmetrical sets having the number of phasors equal to the factors of N [2].

The symmetrical components of an unbalanced set of three phasors (N=3) consist of the followings: three positive-sequence quantities (PSQ), three negative-sequence quantities (NSQ) and three zero-sequence quantities (ZSQ). The PSQ are equal in magnitude and symmetrically displaced by 120°, and have the same phase-sequence as the initial set of phasors. The NSQ are also equal in magnitude and symmetrically displaced by 120°, but have a reversed phase-sequence compared to the initial set of phasors. Lastly, the ZSQ have equal magnitudes and no phase displacement [3], [4]. Fig. 1 shows the graphical representation of the symmetrical components corresponding to an unbalanced set of three related phasors.

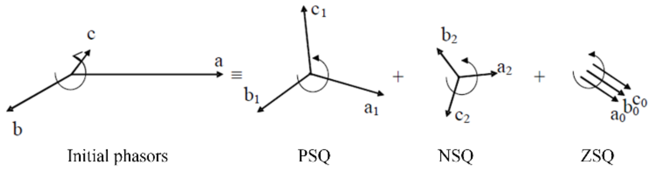

Fig. 1: Symmetrical components of an unbalanced set of three phasors

For a set of three-phase voltages, its corresponding sequence components are obtained using the linear transformation given in (1), while the backward transformation is given in (2).

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \qquad (2)$$

V_a, V_b and V_c are the phase voltages, V_0, V_1 and V_2 are their ZSQ, PSQ and NSQ respectively, referred to *phase a*, and a is the rotation operator given in (3) and which was introduced in the original paper of Fortescue [2].

$$a = 1\angle 120^\circ = -\frac{1}{2} + j \cdot \frac{\sqrt{3}}{2} \qquad (3)$$

The ZSQ, PSQ and NSQ referred to *phase b* and *phase c* can easily be obtained using relation (4) and (5) respectively.

$$\begin{bmatrix} V_{0b} \\ V_{1b} \\ V_{2b} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & a^2 & 0 \\ 0 & 0 & a \end{bmatrix} \cdot \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} V_{0c} \\ V_{1c} \\ V_{2c} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & a^2 \end{bmatrix} \cdot \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \qquad (5)$$

The symmetrical components of a set of three-phase currents can be obtained using relations (1) - (5) by replacing the voltage quantities with currents [3], [4].

Ohm's law correlates the symmetrical components of some related sets of voltages and currents respectively in the same way it correlates the original voltages and currents, and based on this, the sequence impedances can be defined using (6).

$$Z_m = \frac{V_m}{I_m}, \quad m = 0, 1, 2 \qquad (6)$$

V_m and I_m are the symmetrical components of voltage and current respectively, Z_m is their equivalent sequence impedance and m is the index of symmetrical components: 0 for ZSQ, 1 for PSQ and 2 for NSQ [5].

An equivalent sequence network can be defined for each of the three sequence quantities of a three-phase electrical system, with the property that the sequence networks are independent for a balanced system [4]. For an unbalanced system, however, the sequence networks become interconnected, with the connection mode depending on the asymmetry type [5]. Electric faults are classic examples of network asymmetries, so the author uses some of them in Fig. 2 to illustrate the interconnections between the sequence networks of a simple three-phase electrical system under different unbalanced conditions. The equivalent sequence diagram for balanced conditions is also shown. In all cases, the electric source supplies only voltage PSQ, labeled *E* in Fig. 2, thus resembling the commercial synchronous generators, which are designed to produce only PSQ voltages [5].

It is important to note that the symmetrical components are phasors and in practice they are either derived from the phase quantities, after the latter are acquired via Current Transformers (CTs), Voltage Transformers (VTs) and Coupling Capacitor VT (CCVTs), or measured via star-broken-delta transformers and core balance CTs, as could be the case with the ZSQ of voltage and current.

III. SYMMETRICAL COMPONENTS IN ELECTRICAL PROTECTION: A LITERATURE REVIEW

A. *Line protection*

In general, line fault detection is performed by directional, distance, differential, pilot, travelling wave based protection or a combination of them. The method of symmetrical components

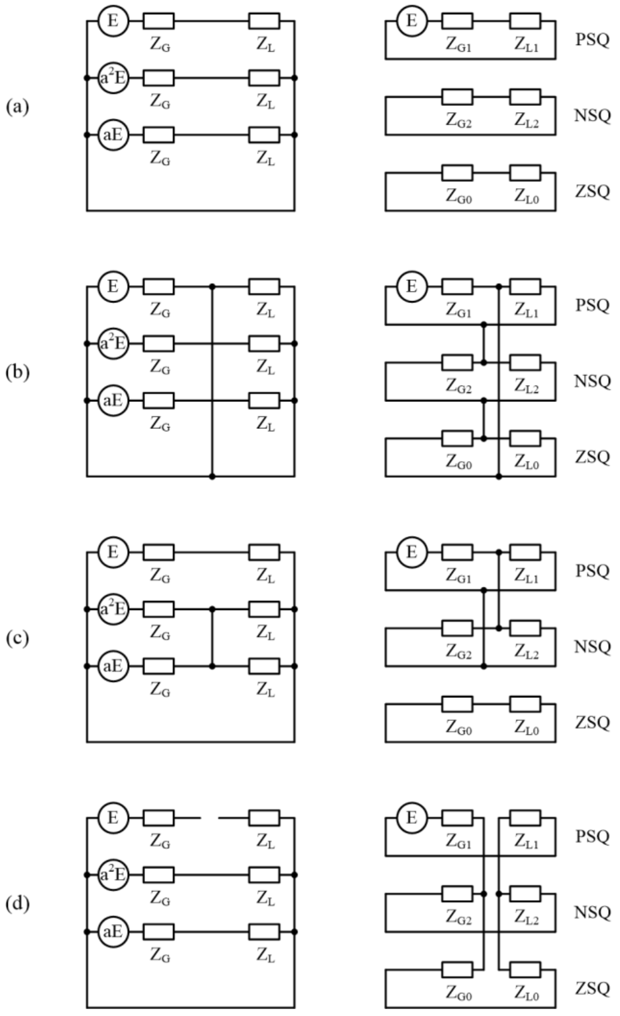

Fig. 2: A three-phase electrical system and its equivalent sequence network for: (a) balanced network conditions, (b) phase-to-ground short-circuit fault, (c) phase-to-phase short-circuit fault, (d) open-phase or broken conductor [5]

is used either to improve these protection functions or to provide new means of line protection. For example, many directional relaying techniques operate on symmetrical components. In [6] a number of such techniques are analyzed for CCVT subsidence transient condition in the high voltage and extra-high voltage transmission lines. The analysis includes two positive-sequence directional relaying methods based on phase angle difference between the superimposed components of voltage PSQ and current PSQ, respectively on phase angle difference between the fault and pre-fault current PSQ. The same analysis also includes two negative-sequence directional relaying algorithms based on phase angle difference between current NSQ and voltage NSQ, respectively on phase angle difference between the fault and pre-fault current NSQ [6].

A positive-sequence directional element that uses the phase angle difference between superimposed components of voltage PSQ and current PSQ has been discussed in [7]-[10] for various protection instances. In [7] it is used as a line directional relay, in [8] it is implemented in a numerical distance relay, whereas in [9] and [10] it is integrated into a directional-comparison pilot protection scheme for lines. The positive-sequence directional element that uses the phase angle difference between the fault and pre-fault current PSQ has been proposed in [11] to overcome the issues of conventional directional relays (based on voltage and current phasors) during voltage and current inversions in series-compensated lines. For current inversions, the decision on fault direction requires, in addition to the directional element, calculation of the change in magnitude of voltage PSQ during the fault at relay location [11].

Negative-sequence directional relaying has been discussed for line protection for many years and is traditionally based on phase angle difference between current NSQ and voltage NSQ. This solution has been adopted in [12] and [13] in a directional pilot protection algorithm for extra-high voltage and ultra-high voltage transmission lines with single-pole tripping. Utilization of the superimposed NSQ of voltage and current is also possible, and has been suggested to eliminate the pre-fault NSQ of voltage and current [13], [14]. Another solution for negative-sequence directional relaying has been proposed in [15] by using the phase angle difference between the fault and pre-fault current NSQ, with the benefit of not requiring voltage information.

Directional elements can also operate on ZSQ, such elements having, in fact, a long history in ground fault protection. In line protection, a zero-sequence directional element can be used as a standalone relay or in a pilot scheme [16]. Such schemes have been discussed in [16], whereas in [17] and [18] the analysis of the incorrect operation events of some zero-sequence directional pilot protection schemes on a double-circuit transmission line has been presented. To determine the ground fault direction, the zero-sequence directional elements use the phase angle between the voltage ZSQ and current ZSQ at relay location [16]-[18] or the phase angle between the current ZSQ and current or voltage at neutral of the supplying transformer [16].

In distance protection, symmetrical components are used by several algorithms. Impedance relays can be polarized by PSQ of voltage [19], [20], fault phase selection schemes are often based on relationships between certain symmetrical components of current [19], [21], while ground distance elements may use zero-sequence current compensation based on current ZSQ and mutual compensation for double-circuit lines based on ZSQ of the current in adjacent line [22], [23]. In [24] a new algorithm for distance relays has been proposed based on an adaptive neuro fuzzy inference system that uses voltage PSQ and current PSQ as inputs. It is shown that the real and imaginary parts of voltage PSQ and current PSQ are functions of the fault distance and each fault location is characterized by a unique set of these quantities, the proposed algorithm relying on this property to discriminate faults inside and outside the protection zone [24]. In [25] a comparison has been made between a modern distance relay and a distance relay that uses an algorithm based on PSQ of current, PSQ, NSQ and ZSQ of voltage and involves the assessment of a single equation for all types of line faults. The latter was first proposed during 1970s to reduce the computational burden of electronic relays, but its performance is inferior to a modern distance relay, while the available computational power is no longer critical [25].

Symmetrical components can also be used in line differential protection. For example, negative-sequence differential schemes have been applied to line protection for many years [26]. These schemes follow the current differential principle, but apply it to the NSQ of the currents entering and leaving the protected zone, not to the phase currents [26]. In [27] and [28], a CT saturation detection algorithm for line differential relays has been proposed based on ZSQ of differential currents. The instant of a significant rate of change on ZSQ of differential currents relative to the bias current marks the start of CT saturation, while the polarity of this gradient distinguishes an in-zone fault from an external fault that causes the CT saturation [27], [28].

Some authors have advanced other line protection schemes that use information about symmetrical components of certain electric quantities at the two line ends. In [29] a fault localization algorithm based on PSQ and NSQ of voltages and currents at both ends of the line has been presented. It uses quoted quantities and Kirchhoff theorems to estimate distance to fault, expressed as a percentage of total line length with relatively small errors for low fault resistances, and observation of the current sequence components to determine the type of fault [29]. In [30] a fault detection technique has been developed based on PSQ of the reactive power, which is a function of the line reactance and the voltage PSQ at both ends of the transmission line. It is shown that the fault is indicated by the same sign for PSQ of reactive power at the two line ends, while the fault type is indicated by evaluating a set of criteria based on symmetrical components of voltage and current [30]. In [31] a negative-sequence directional comparison scheme has been proposed in which the line status is judged by comparing the direction of the current NSQ at one end of the line with respect to the direction of the current NSQ at the other end of the line. A faulted line is indicated by opposite directions for the NSQ of the currents at the two line ends, while the current NSQ magnitudes should also exceed a predefined threshold to avoid false tripping [31].

B. Transformer protection

Differential protection is the primary means of protection for high power transformers and is a widely discussed topic in the literature. The operation of transformer differential protection is not always optimal and have been suggested methods to improve it or replace it using symmetrical components. There have been mentioned in this paper a negative-sequence differential scheme and a negative-sequence directional comparison scheme for line protection based on current NSQ [26], [31], but such schemes have also been applied to transformers, mainly due to increased sensitivity to inter-turn faults compared to traditional differential schemes [32]. The negative-sequence differential protection for power transformers has been described in [26], [32], and consists essentially on the conventional percentage restrained principle applied to the NSQ of the zone currents. This approach could be used either as a standalone protection solution or as an add-on to traditional differential relays [26], [32]. The negative-sequence directional comparison schemes for transformer protection rely for internal/external discrimination on phase angle comparison between the NSQ of the zone currents once the NSQ magnitudes exceed a preset value and require turns-ratio and vector-group compensation. An internal fault is indicated by a phase angle mismatch of the NSQ of the zone currents, subject, of course, to some tolerance [31]-[34]. This approach has been proposed to mitigate the issue of delayed tripping for traditional differential relays during power system oscillations [31] and to improve the detection of minor inter-turn winding faults [33], [34]. In [34], the inter-turn fault detection was further improved by adding a voltage percentage differential algorithm that uses the NSQ of the primary and secondary voltages of transformer, and which is sensitive to inter-turn winding faults even during the transformer energization.

In the literature have also been presented a positive-sequence differential scheme [35], [36] and a zero-sequence differential scheme [36] based on the conventional percentage restrained principle applied to the PSQ, respectively the ZSQ of the zone currents. In [35] the positive-sequence differential scheme has been proposed for transformer protection and it includes an inrush-block element and an overfluxing-block element based on the PSQ of the second and fifth harmonics of the differential currents. In [36] a comparative analysis has been performed between the conventional percentage differential scheme and the percentage differential schemes based on PSQ, NSQ and ZSQ of the currents on the two sides of the transformers, the study highlighting the potential benefits of each.

Other algorithms for protection of power transformers based on symmetrical components were advanced in [37]-[40]. In [37], the authors have been suggesting an algorithm that combines a negative-sequence differential scheme and a positive-sequence directional scheme, so that an internal fault is indicated if the difference on magnitude between the NSQ of the currents on the two sides of transformer, and the phase angle difference between the PSQ of the same currents, exceed certain limits [37]. In [38], the authors proposed an algorithm that uses the NSQ of voltage and current on both sides of the transformer to compute their equivalent negative-sequence impedances. With the quantities on secondary side of transformer referred to primary side, an internal fault is indicated by relatively large differences between the negative-sequence impedances, respectively between the NSQ of the currents on the two sides of transformer [38]. In [39], the authors have been suggesting the use of positive-sequence admittances at the two sides of transformer, calculated based on the current PSQ and voltage PSQ, for the identification of fault events. It has been shown that the location on a specific quadrant of the accumulated positive-sequence admittances indicates the event type, so the proposed algorithm uses this information to trip for internal faults [39]. In [40], a new inrush restraining algorithm for differential protection of transformers has been proposed, in which the second harmonic restraint is disabled upon detection of a significant negative-sequence power, as the authors suggested that such condition is not characteristic to transformer energization. The negative-sequence power was calculated using the voltage NSQ at primary side of transformer and the NSQ of the differential currents [40].

In [41] and [42], the authors have proposed utilization of a criterion based on PSQ and NSQ of the differential currents to discriminate internal faults of power transformers from external faults and other transient conditions. In [41], the internal fault is indicated by the drop below a preset threshold of the ratio between difference and sum of the squared magnitudes of PSQ and NSQ of the differential currents. In [42], the internal fault is indicated by the increase above a preset threshold of the ratio between the magnitudes of NSQ and PSQ of the differential currents. In [43], the same ratio as in [42], but calculated for the currents on primary side of transformer, has been proposed for detection of transformer faults, indicated, in this case as well, by the increase above a preset threshold of the proposed ratio.

C. *Protection of electrical machines*

Due to the adverse effects of open-phase faults and system unbalances on electrical machines, the equipment is protected against such conditions, often using symmetrical components. This kind of protection includes overcurrent elements operating on current NSQ [44], [45], overvoltage elements operating on voltage NSQ [44], [46], directional power elements monitoring on negative-sequence power [26], [47] and elements tripping on a significant ratio of symmetrical components, such as between voltage NSQ and voltage PSQ, or between current NSQ and current PSQ [48].

The use of symmetrical components in machine protection is not limited only to the detection of open-phase faults and unbalance system conditions. In [49], the neutral overvoltage relay of a high-impedance grounded synchronous generator has been prevented to maloperate for a ground fault on the high voltage side of the step-up transformer due to the zero-sequence voltage coupling by using the current NSQ of generator as a restraint quantity. Using this approach it is possible to improve the speed and security of the stator ground fault protection for such generators under the conditions described [49]. In [50], a negative-sequence impedance directional protection algorithm for protection of turbo-generator stator has been developed. The proposed protection algorithm relies on the fact that the angle of the equivalent negative-sequence impedance, calculated using the NSQ of voltage and current at generator terminals, indicate whether these NSQ are produced externally or by an internal stator fault [50]. In [51] and [52] a zero-sequence differential protection scheme for detection of stator ground faults based on superimposed voltage ZSQ measured at generator terminals and at generator neutral has been advanced. The proposed scheme is based on the fact that internal ground faults cause equal voltage ZSQ at generator terminals and generator neutral, while external faults do not [51], [52]. In [26], the authors derived a stator-rotor unbalance element and a stator-rotor current differential element for protection of synchronous machines against inter-turn faults. The two elements are based on the ampere-turn balance between the fields created by the NSQ of stator current and by the rotor double-frequency current, being sensitive to both stator and rotor inter-turn faults [26].

D. *Protection of distribution networks*

Distribution networks are generally protected against phase faults by phase overcurrent relays and against ground faults by ground fault relays. From a theoretical perspective, it could be argued that all ground relays operate on ZSQ. These include overcurrent elements operating on current ZSQ, zero-sequence directional elements operating on current ZSQ and voltage ZSQ, overvoltage elements operating on voltage ZSQ and wattmetric relays using zero-sequence energy [53], [54]. However, ground fault protection could also be based on NSQ, as shown in [53], where the authors have presented the principles for the detection of ground faults using negative-sequence overcurrent elements, negative-sequence directional elements and negative-sequence current differential protection. On the other hand, overcurrent elements operating on current NSQ have been used for a long time in phase fault protection [55].

In [56], the authors have been discussing the situation of multiple phase-to-ground faults occurring in a low resistance grounded distribution network, which may cause a significant decrease of the current ZSQ in the faulted feeders and a possible lack of tripping for zero-sequence overcurrent relays. To solve this problem, an adaptive protection algorithm was proposed, in which the settings of zero-sequence overcurrent relays installed on distribution feeders are adjusted using voltage at the supply busbar and current ZSQ at the relay location [56]. In [57], the authors have proposed an adaptive zero-sequence overvoltage algorithm for ground faults in ungrounded distribution networks, in which the tripping of zero-sequence overvoltage relays is accelerated by a signal proportional to the current NSQ at relay location. In this way, the zero-sequence overvoltage relays on faulty feeders will trip faster because the current NSQ are larger in such feeders [57]. In [58], a zero-sequence differential scheme has been advanced for feeder protection in distribution networks grounded via an arc suppression coil. The scheme compares the difference between the current ZSQ entering and leaving the protected feeder with the capacitive current expected on that section and then decides on tripping or not tripping accordingly [58]. In [59], a fault classification algorithm based on a neural network has been developed to distinguish between open-phase faults and short-circuit faults in distribution networks in order to control the reclosers operation accordingly. The algorithm uses the symmetrical components of pre-fault currents and the NSQ and ZSQ of fault current [59].

In [60] and [61], the authors have proposed utilization of a criterion based on PSQ and NSQ of the phase currents to help overcurrent protection in a distribution network to discriminate a short-circuit fault from other abnormal conditions, such as motor starting or transformer energization. In both papers, the fault is indicated by the drop below a preset threshold of the ratio between difference and sum of the magnitudes of current PSQ and current NSQ. The threshold is set in such way that motor starting and transformer energization will not trigger the relay tripping [60], [61].

E. *Microgrid protection*

A microgrid represents a distribution network that includes distributed generators and consumers, and it can operate either in a grid-connected mode or in an islanded mode. Microgrids are typically characterized by bidirectional power flow, variability of fault currents and reduced short-circuit power when operating in the islanded mode. Any protection system needs to address all these challenges in a microgrid.

The development of appropriate protection algorithms for microgrid protection has been the focus of many studies, some authors suggesting the use of symmetrical components for this purpose. In [62], the authors have proposed a protection scheme for microgrids that uses current NSQ to detect phase-to-phase faults and current ZSQ to detect phase-to-ground faults. If the magnitude of a symmetrical component exceeds a predefined pick-up value, then its corresponding fault is detected and a trip command is issued. The scheme needs coordination between the unbalanced loads and current NSQ. A similar scheme has been proposed in [63], but this one also includes a negative-sequence directional element to distinguish the forward and reverse faults, based on the phase angle difference between the NSQ of voltage and current. In [64], a negative-sequence directional element using the same concept as in [63] has been applied in a microgrid protection that also includes positive-sequence directional elements and zero-sequence directional elements based on phase angle differences between the PSQ, respectively ZSQ of voltage and current.

In [65], a directional adaptive overcurrent algorithm based on symmetrical components of current has been advanced for protection of a microgrid. The phase angle difference between the superimposed current NSQ and pre-fault current NSQ is used to indicate the direction of an asymmetric fault, while the phase angle difference between the superimposed current PSQ and pre-fault current PSQ is used to indicate the direction of a three-phase fault. The operating quantity of the overcurrent elements is adaptive to network conditions, as it is a function of the current sequence components [65]. The same approach for a positive-sequence directional element as in [65] has also been proposed in [66] for detection of fault direction in a distribution network with distributed generators. In [67], a protection scheme for microgrids comprising from positive-sequence undervoltage elements and positive-sequence directional elements has been advanced. All of the indicated elements have been based on the superimposed values of voltage and current in order to minimize the load effect on protection, and their operation is coordinated in order to achieve selective tripping [67]. Another way to obtain coordinated relay tripping is by using a communication channel between the relays. Precisely this approach has been advanced in [68], as the authors proposed a microgrid protection scheme consisting of negative-sequence directional elements, operating on phase angle difference between the voltage NSQ and current NSQ, and the use of a communication infrastructure to trip only the faulted section of the microgrid.

Another protection concept for microgrids and distribution networks with distributed generators has been introduced in [69] and [70] by comparing the positive-sequence impedance seen by a relay during the fault with the positive-sequence impedance seen in the absence of the fault and using the discrepancies as a fault indicator. The positive-sequence impedance is computed by the relay using the voltage PSQ and current PSQ at relay location [69], [70]. The same protection concept has also been used in [71] in combination with a positive-sequence directional element for protection of a distribution network with distributed generators.

In [72], the authors have developed an islanding detection algorithm for distributed synchronous generators using the NSQ voltage and its damping patterns. Such protection is essential in microgrid applications due to safety and security reasons.

In [73] and [74], the authors have proposed an adaptive overcurrent scheme based on the superimposed values of current PSQ, current NSQ and voltage PSQ for protection of the wind turbines in a large wind farm. The relations between the current PSQ and current NSQ are used to detect the fault type, while the relations between the current PSQ and voltage PSQ are used to detect the fault direction. Then, based on all this information, the operation of adaptive overcurrent relays is suitably adjusted, with each relay capable of instant tripping, delayed tripping or no tripping at all [73], [74].

IV. CONCLUSIONS

This paper presented a review of the publications that have proposed or discussed the use of symmetrical components in electrical protection. Due to the large number of publications, it was impossible to carry out a complete literature review, so the possibility of future work remains. However, a sufficiently large number of publications has been reviewed in order to cover the core of symmetrical component based protection relaying. The use of symmetrical components in electrical protection includes, but it is not limited to overcurrent and overvoltage elements, directional algorithms, distance relaying, differential schemes, adaptive protection techniques and fault detection algorithms based on relationships of symmetrical components. All these are used for protection of a wide range of applications, from power systems and high voltage equipment to distribution networks, microgrids and end-user equipment. Table I summarizes the revised protection techniques that use symmetrical components and the main types of applications where they are applied.

To conclude, the method of symmetrical components has been used in electrical protection for a long time and will be used in the future as well because it represents the basis of several protection systems. The modern relays allow the implementation of protection algorithms based on symmetrical components in all types of electrical systems, thus potentially providing better solutions to old protection problems, or new solutions to new challenges, such as microgrid protection. In any case, literature analysis indicates a high relevance of symmetrical components in electrical protection.

REFERENCES

[1] F. A. Furfari and J. Brittain, “Charles LeGeyt Fortescue and the Method of Symmetrical Components,” *IEEE Industry Applications Magazine*, pp. 7-9, Volume 8, Issue 3 May - June 2002.

[2] C. Fortescue, “Method of symmetrical co-ordinates applied to the solution of polyphase networks,” in *34th Annual Convention of the American Institute of Electrical Engineers*, Atlantic City, NJ, USA, 1918.

[3] J. Blackburn, Protective relaying: principles and applications, New York, NY, USA: Marcel Dekker, 1987.

TABLE I. Overview of revised protection techniques based on symmetrical components

Application	**Reference**	**Protection/Topic**
Transmission lines	[6]-[18]	positive-sequence, negative-sequence and zero-sequence directional elements
	[19]-[25]	distance relaying and related topics, including fault phase selectors, zero-sequence compensation, symmetrical component based distance relay
	[26]-[31]	algorithms for differential protection and CT saturation detection, fault localization and line-ends comparison protection schemes
Power transformers	[26], [31]-[37]	differential algorithms and direction-comparison protection schemes for detection of transformer internal faults
	[38]-[43]	various techniques, including equivalent impedance/admittance based protection, inrush detection algorithms and internal/external fault discrimination methods
Electrical machines	[44]-[48]	protection algorithms for unbalance and open-phase conditions
	[26], [49]-[52]	protection algorithms for inter-turn faults in stator and rotor
Distribution networks	[53]-[58]	phase and ground fault protection based on overcurrent, overvoltage, directional and differential elements
	[59]-[61]	fault classification schemes and algorithms for discrimination of electric faults from other transients
Microgrids	[62]-[68]	phase and ground fault protection based on overcurrent, undervoltage and directional overcurrent elements
	[69]-[74]	equivalent impedance based protection, anti-islanding detection, adaptive overcurrent protection and fault localization for wind farms

[4] J. Blackburn, Symmetrical components for power systems engineering, New York, NY, USA: Marcel Dekker, Inc., 1993.

[5] The Electricity Council, Power system protection, volume 1, Stevenage, UK: Peter Peregrinus Ltd., 1990.

[6] M. Biswal and S. Biswal, “A positive-sequence current based directional relaying approach for CCVT subsidence transient condition,” *Protection and Control of Modern Power Systems,* vol. 2, no. 8, 2017.

[7] J. L. Suonan, Q. Q. Xu, G. B. Song and Y. Wu, “A reliable directional relay based on positive sequence compensated voltage and current components,” in *IEE International Conference on Developments in Power System Protection*, Amsterdam, Netherlands, 2004.

[8] P. G. McLaren, E. Dirks, R. P. Jayasinghe, I. Fernando, G. W. Swift and Z. Zhang, “A positive sequence directional element for numerical distance relays,” in *IEEE Communications, Power and Computing Conference*, Winnipeg, Canada, 1995.

[9] H. Gao and P. A. Crossley, “Directional relay for EHV transmission lines using positive-sequence fault components,” in *IEEE Russia Power Tech*, St. Petersburg, Russia, 2005.

[10] H. Gao and P. A. Crossley, “Design and evaluation of a directional algorithm for transmission-line protection based on positive-sequence fault components,” *IEE Proceedings - Generation, Transmission and Distribution,* vol. 153, no. 6, pp. 711 - 718, 2006.

[11] P. Jena and A. K. Pradhan, “A positive-sequence directional relaying algorithm for series-compensated line,” *IEEE Transactions on Power Delivery,* vol. 25, no. 4, pp. 2288 - 2298, 2010.

[12] B. Wang, X. Dong, Z. Bo and A. Klimek, “Performance of negative sequence pilot protection applications in transmission line with open-phase operation,” in *Transmission & Distribution Conference & Exposition: Asia and Pacific*, Seoul, South Korea, 2009.

[13] B. Wang, X. Dong, Z. Bo and A. Klimek, “Negative-Sequence pilot protection with applications in open-phase transmission lines,” *IEEE Transactions on Power Delivery,* vol. 25, no. 3, pp. 1306 - 1313, 2010.

[14] P. Jena and A. K. Pradhan, “Directional relaying during secondary arc using negative-sequence superimposed technique,” *IEEE Transactions on Power Delivery,* vol. 30, no. 3, pp. 1626 - 1628, 2015.

[15] P. Jena and A. K. Pradhan, “Directional relaying during single-pole tripping using phase change in negative-sequence current,” *IEEE Transactions on Power Delivery,* vol. 28, no. 3, pp. 1548 - 1557, 2013.

[16] Y. Xue, J. Zeek, M. Thakhar, M. Zhang and W. Zhang, “Ground fault protection of pilot schemes: basics and applications,” in *Western Protective Relay Conference*, Spokane, WA, USA, 2013.

[17] G. Zeng, Z. Cai, M. Huang and Z. Liu, “Analysis and countermeasures of misoperation of zero sequence pilot protection on circuit lines of same pole,” in *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, China, 2008.

[18] X. Jiang, D. Du, X. Wang and Z. Li, “Maloperation prevention study of zero sequence direction protection to broken-line faults of parallel circuits on same tower,” in *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Changsha, China, 2015.

[19] B. Kasztenny and D. Finney, “Fundamentals of distance protection,” in *Annual Conference for Protective Relay Engineers*, College Station, TX, USA, 2008.

[20] Q. H. Li, Y. J. Zhang, W. P. Yuan and F. Li, “A study on influence of wind power on positive sequence voltage polarized impedance relay,” in *IEEE Power Engineering and Automation Conference*, Wuhan, China, 2012.

[21] W. Li, T. Bi and Q. Yang, “Study on sequence component based fault phase selector during power swings,” in *International Conference on Critical Infrastructure,* Beijing, China, 2010.

[22] T. Kase and P. G. Beaumont, “Zero sequence current compensation for distance protection applied to series compensated parallel lines,” in *Cigré Study Committee B5 Colloquium*, Calgary, Canada, 2005.

[23] H. Seyedi, S. Teimourzadeh and P. S. Nezhad, “Adaptive zero sequence compensation algorithm for double-circuit transmission line protection,” *IET Generation, Transmission & Distribution,* vol. 8, no. 6, pp. 1107 - 1116, 2014.

[24] H. Khorashadi-Zadeh and Z. Li, “Transmission line distance protection using ANFIS and positive-sequence components,” in *iREP Symposium - Bulk Power System Dynamics and Control - VII. Revitalizing Operational Reliability*, Charleston, USA, 2007.

[25] C. Venkatesh and K. S. Swarup, “Investigating performance of symmetrical components of distance relay,” in *National Power System Conference*, Varanasi, India. , 2012.

[26] B. Kasztenny, N. Fischer and H. J. Altuve, “Negative-sequence differential protection – principles, sensitivity and security,” in *Annual Conference for Protective Relay Engineers*, College Station, USA, 2015.

[27] N. Villamagna, P. A. Crossley and H. Y. Li, “Design of a symmetrical component based current differential protection scheme,” in *IEEE Bologna PowerTech Conference*, Bologna, Italy, 2003.

[28] N. Villamagna and P. A. Crossley, “A CT saturation detection algorithm using symmetrical components for current differential protection,” *IEEE Transactions on Power Delivery,* vol. 21, no. 1, pp. 38 - 45, 2006.

[29] C. Purushotham Reddy, D. V. S. S. Siva Sarma and O. V. S. R. Varaprasad, “A novel fault classifier and locator using one-end current spectrum and minimal synchronized symmetrical components for transmission lines,” in *IEEE Annual India Conference*, Bangalore, India, 2016.

[30] A. Rahmati and R. Adhami, “A fault detection and classification technique based on sequential components,” *IEEE Transactions on Industry Applications,* vol. 50, no. 6, pp. 4202-4209, 2014.

[31] H. Li, C. Zhou, Z. Zhan and Z. Ju, “Fault identification method during oscillating based on negative sequence directional element,” in *International Conference on Power System Technology,* Chengdu, China, 2014.

[32] L. M. R. Oliveira and J. M. Cardoso, “Comparing power transformer turn-to-turn faults protection methods: negative-sequence component versus space vector algorithms,” *IEEE Transactions on Industry Applications,* vol. 53, no. 3, pp. 2817 - 2825, 2017.

[33] M. Babiy, R. Gokaraju and J. C. Garcia, “Turn-to-turn fault detection in transformers using negative-sequence currents,” in *IEEE Electrical Power and Energy Conference*, Winnipeg, Canada, 2011.

[34] D. Zacharias and R. Gokaraju, “Prototype of a negative-sequence turn-to-turn fault detection scheme for transformers,” *IEEE Transactions on Power Delivery,* vol. 31, no. 1, pp. 122 - 129, 2016.

[35] H. K. Zadeh, “Transformer differential protection using positive-sequence current; design and implementation,” in *IEEE Russia Power Tech*, St. Petersburg, Russia, 2005.

[36] N. Zhang, X. Dong, Z. Bo and A. Klimek, “Performance comparison of current differential protection scheme based on symmetrical components,” in *International Universities Power Engineering Conference*, Brighton, UK, 2007.

[37] D. D. Patel, N. G. Chothani and K. D. Mistry, “Sequence component of currents based differential protection of power transformer,” in *Annual IEEE India Conference*, New Delhi, India, 2015.

[38] P. A. Venikar, M. S. Ballal and B. S. Umre, “Symmetrical components based advanced scheme for detection of incipient inter-turn fault in transformer,” in *International Conference on Condition Assessment Techniques in Electrical Systems*, Bangalore, India, 2015.

[39] M. M. Eissa, E. H. Shehab-Eldin, M. E. Masoud and A. S. Abd-Elatif, “Digital technique for power transformer fault detection based on positive sequence admittance approach,” in *International Middle-East Power System Conference*, Aswan, Egypt, 2008.

[40] K. Tian and P. Liu, “Improved operation of differential protection of power transformers for internal faults based on negative-sequence power,” in *International Conference on Energy Management and Power Delivery*, Singapore, 1998.

[41] H. Abniki, A. Majzoobi, H. Monsef, H. Dashti, H. Ahmadi and P. Khajavi, “Identifying inrush currents from internal faults using symmetrical components in power transformers,” in *Modern Electric Power Systems Conference*, Wroclaw, Poland, 2010.

[42] D. I. Ivanchenko and B. A. Aleksey, “Transformer fault analysis using instantaneous symmetrical components,” in *IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering*, Moscow, Russia, 2018.

[43] F. J. Nepveux, “Using negative-sequence current to detect line-to-line faults in transformers,” in *IEEE Pulp, Paper & Forest Industries Conference*, Austin, USA, 2016.

[44] D. S. Batorowicz, J. Hanson, O. Goieva, W. Schoenberger and A. Shustov, “Impact of open-phase fault conditions on electrical protection and motor behaviour,” in *IET International Conference on Development in Power System Protection*, Edinburgh, UK, 2016.

[45] M. Dupuis, N. Mahoney, A. Padmanabhan and K. Bhuvaneshwaran, “Negative-sequence overcurrent considerations for induction motor loads,” in *Annual Conference for Protective Relay Engineers*, College Station, USA, 2017 .

[46] A. Hannah, “Negative-sequence relay protection for blown high-side transformer fuse detection,” *IEEE Transactions on Industry Applications*, vol. 35, no. 1, pp. 183 - 189, 1999.

[47] L. Shiming, Y. Xianggen, C. Deshu and T. Huiliang, “Fault component negative-sequence energy direction protection for generators,” in *IEEE Power Engineering Society Winter Meeting. Conference* , Singapore, 2000.

[48] U. Ajmal, H. Ha, S. Subramanian and V. A., “HV open phase detection method based on symmetrical components,” in *2016 Cigre Session*, Paris, France, 2016.

[49] R. W. Patterson and A. Eltom, “A practical improvement to stator ground fault protection using negative sequence current,” in *IEEE Power & Energy Society General Meeting*, Vancouver, Canada, 2013.

[50] H. Liangliang, S. Yuguang and Q. Arui, “Analysis on the negative sequence impedance directional protection for stator internal fault of turbo generator,” in *International Conference on Electrical Machines and Systems*, Incheon, South Korea, 2010.

[51] T. Nengling and J. Stenzel, “Differential protection based on zero-sequence voltages for generator stator ground fault,” *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 116 - 121, 2007.

[52] N. L. Tai and Q. Ai, “Protection technique based on delta-zero sequence voltages for generator stator ground fault,” *IEE Proceedings - Generation, Transmission and Distribution*, vol. 151, no. 5, pp. 651 - 657, 2004.

[53] X. Zeng, K. K. Li, W. L. Chan and X. Yin, “Novel techniques for earth fault feeder detection based on negative-sequence current in industry power systems,” in *IEEE Industry Applications Conference*, Chicago, USA, 2001.

[54] L. Mu and Q. Meng, “Ground-fault protection based on active component of zero-sequence current in resistance neutral grounded distribution systems,” in *IEEE Region 10 Conference on Computers, Communications, Control and Power Engineering*, Beijing, China, 2002.

[55] F. Elneweihi. A., E. O. Schweitzer and M. W. Feltis, “Negative-sequence overcurrent element application and coordination in distribution protection,” *IEEE Transactions on Power Delivery*, vol. 8, no. 3, pp. 915 - 924, 1993.

[56] X. Guo, B. Han, J. Lei and G. Wang, “A novel adaptive zero-sequence current protection for low resistance grounding system,” in *IEEE PES Asia-Pacific Power and Energy Conference*, Xi'an, China, 2016.

[57] X. Lin, Z. Zhao and Z. Bo, “An adaptive inverse time-delay characteristic of the zero-sequence overvoltage protection for identification of the single-phase earth fault in the neutral non-effectively grounded power systems,” in *IEEE Power & Energy Society General Meeting*, Calgary, Canada, 2009.

[58] X. Lin, I. Kursan, J. Sun, Z. Li, R. Zheng, Z. Bo, J. Xu and Z. Wei, “Fault section identification based on per-unit zero-sequence current,” in *IET International Conference on Developments in Power System Protection*, Copenhagen, Denmark, 2014.

[59] A. R. Oliveira, P. A. N. Garcia, L. W. Oliveira and J. L. R. Pereira, “Distribution system to fault classification using negative-sequence and intelligent system,” in *International Conference on Intelligent System Applications to Power Systems*, Hersonissos, Greece, 2011.

[60] S. Lotfi-fard, J. Faiz and R. Iravani, “Improved overcurrent protection using symmetrical components,” *IEEE Transactions on Power Delivery*, vol. 22, no. 2, pp. 843-850, 2007.

[61] M. D. Borkar and K. D. Thakur, “Analysis of unsymmetrical fault using symmetrical component for improvement of overcurrent protection scheme,” in *International Conference on Computer Communication and Informatics*, Coimbatore, India, 2013.

[62] H. Nikkhajoei and R. Lasseter, “Microgrid protection,” in *IEEE Power Engineering Society General Meeting*, Tampa, FL, USA, 2007.

[63] M. Zamani, T. Sidhu and A. Yazdani, “A protection strategy and microprocessor-based relay for low-voltage microgrids,” *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1873-1883, 2011.

[64] M. Zamani, T. Yazdani and A. Sidhu, “A communication-assisted protection strategy for inverter-based medium-voltage microgrids,” *IEEE Transactions on Smart Grids*, vol. 3, no. 4, pp. 2088-2099, 2012.

[65] H. Muda and P. Jena, “Superimposed adaptive sequence current based microgrid protection: a new technique,” *IEEE Transactions on Power Delivery*, vol. 32, no. 2, pp. 757-767, 2017.

[66] S. Tian, Y. Liu and G. Mei, “New theory of directional current protection for the distribution network containing DG based on fault component,” in *International Conference on Advanced Power System Automation and Protection*, Beijing, China, 2011.

[67] A. V. Eluvathingal and K. S. Swarup, “Instantaneous symmetrical components based microgrid interface protection relay,” in *International Conference on Power Systems (ICPS)*, Pune, India, 2017.

[68] G. G. Karady and P. Mandava, “Pilot directional protection using negative sequence directional element,” in *Clemson University Power Systems Conference*, Clemson, USA, 2014.

[69] S. Mirsaeidi, D. M. Said, M. W. Mustafa and M. H. Habibuddin, “A protection strategy for micro-grids based on positive-sequence component,” *IET Renewable Power Generation*, vol. 9, no. 6, pp. 600 - 609, 2015.

[70] M. Xu, G. Zou, C. Xu, W. Sun and S. Mu, “Positive-sequence differential impedance protection for distribution network with IBDGs,” in *IEEE International Conference on Power System Technology* , Wollongong, Australia, 2016.

[71] W. Huang, N. Tai, K. Li, X. Zheng and S. Chen, “Protection scheme for active distribution networks using positive-sequence components,” in *IEEE Power & Energy Society General Meeting*, Denver, USA, 2015.

[72] A. Helmzadeh, J. Sadeh and O. A. Musavi, “Anti-islanding protection of distributed generation resources using negative-sequence component of voltage,” in *International Conference on Power Engineering, Energy and Electrical Drives* , Setubal, Portugal, 2007.

[73] T. Y. Zheng, S. T. Cha, P. A. Crossley and Y. C. Kang, “Protection algorithm for a wind turbine generator based on positive- and negative-sequence fault components,” in *International Conference on Advanced Power System Automation and Protection*, Beijing, China, 2011.

[74] T. Zheng, S. Cha, B. Lee, P. Crossley, M. Song og Y. Kang, »Design and evaluation of a protection algorithm for a wind turbine generator based on the fault-generated symmetrical components,« i *2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*, Manchester, UK, 2011.