The Use of Symmetrical Components in Electrical Protection

by

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Agenda

- Introduction
- Overview of symmetrical components
- Symmetrical components in electrical protection
    - line protection
    - transformer protection
    - protection of electrical machines
    - protection of distribution networks
    - microgrid protection
- Conclusion

- **Introduction**
- Overview of symmetrical components
- Symmetrical components in electrical protection
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Introduction

- the method of symmetrical components was introduced by engineer Charles LeGeyt Fortescue at the 1918 edition of the Annual Convention of the American Institute of Electrical Engineers

- the method is an important tool in electrical engineering, simplifying the analysis of multi-phase electrical circuits operating under unbalanced conditions

- the applications of the method of symmetrical components include short-circuit calculations for power system planning and power system protection studies

- some protection systems operate on symmetrical components, as these quantities are more sensitive to fault conditions compared to phase voltage/current

Introduction

- the advancement of numerical relays allows the implementation of more complex protection systems that use the method of symmetrical components

- there is a relatively large number of technical papers discussing protection algorithms and protection schemes based on the method of symmetrical components

- these papers cover many types of applications, from high voltage power systems and high voltage equipment to distribution networks and end-user equipment

- the present paper/presentation presents a short review of the most relevant technical papers regarding the use of symmetrical components in protection relaying

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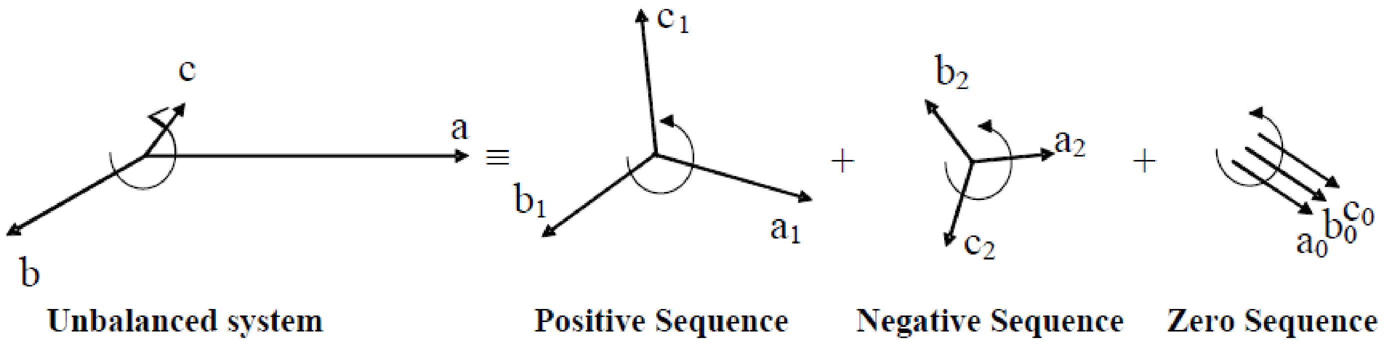
Overview of symmetrical components

- any 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, named the symmetrical components of the initial set of phasors

- the symmetrical components of an unbalanced set of three phasors (*N=3*), consist from:
  - 3 positive-sequence quantities (PSQ), equal in magnitude, symmetrical displaced by 120° and with the same phase-sequence as the initial set of phasors
  - 3 negative-sequence quantities (NSQ), equal in magnitude, symmetrical displaced by 120° and with reversed phase-sequence compared to the initial set of phasors
  - 3 zero-sequence quantities (ZSQ), equal in magnitude and without phase displacement

Overview of symmetrical components



abc-012 transformation:

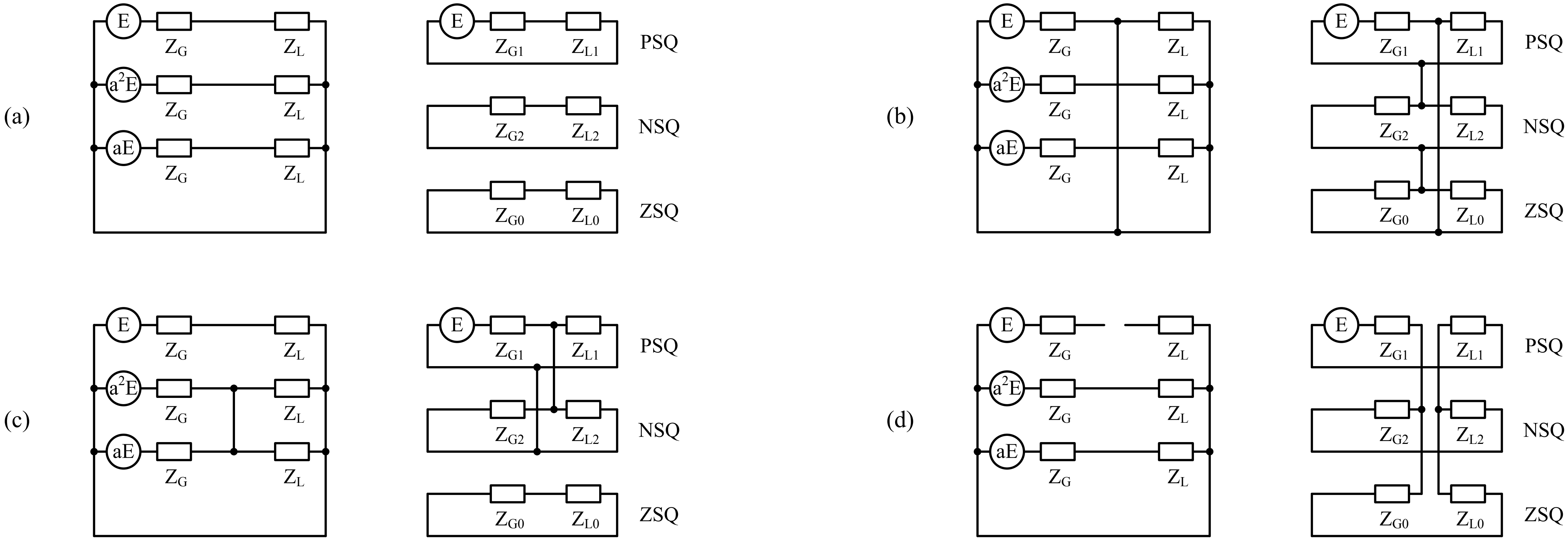
$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$a = 1\angle 120° = -\frac{1}{2} + j \cdot \frac{\sqrt{3}}{2}$$

Sequence impedance:

$$Z_m = \frac{V_m}{I_m}, \quad m = 0,1,2$$

Overview of symmetrical components



(a) No fault; (b) Phase-ground fault; c) Phase-phase fault; d) Open-phase fault;

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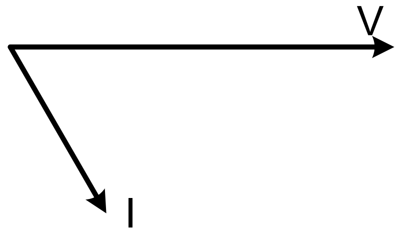
Symmetrical components in electrical protection

Line protection



- directional elements, based on phase angle difference of:
    - voltage NSQ and current NSQ
    - superimposed components of voltage NSQ and current NSQ
    - fault current NSQ and pre-fault current NSQ
    - voltage ZSQ and current ZSQ
    - current ZSQ at relay location and voltage at transformer neutral
    - superimposed components of voltage PSQ and current PSQ
    - fault current PSQ and pre-fault current PSQ

Symmetrical components in electrical protection

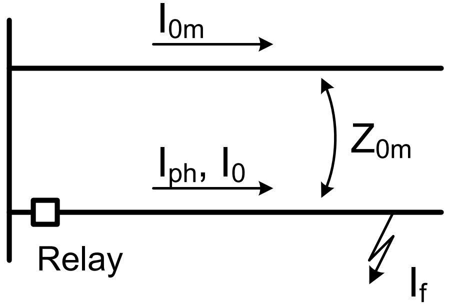
Line protection

- distance relays
  - polarized by voltage PSQ
  - fault phase selection schemes based on current seq. comp.

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Example: AG fault: $I_b=I_c=0$, $\angle(I_0,I_2)=0°$; BG fault: $I_a=I_c=0°$, $\angle(I_0,I_2)=120°$;
AB fault: $I_a=-I_b$, $\angle(I_1,I_2)=60°$; BC fault: $I_b=-I_c$, $\angle(I_1,I_2)=180°$;

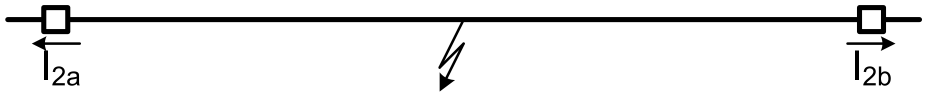
  - zero-sequence current compensation in ground distance elements
  - zero-sequence mutual compensation for double-circuit lines



Symmetrical components in electrical protection

Line protection

- negative-sequence differential schemes
  - differential principle applied to current NSQ entering and leaving the protected zone
- directional-comparison schemes:
  - comparing the direction of PSQ of reactive power at the two line ends
  - comparing the direction of current NSQ at the two line ends
  - in both cases a fault is indicated by opposite directions of the monitored quantities



Symmetrical components in electrical protection

Transformer protection

- negative-sequence differential schemes
  - percentage restrained principle applied to NSQ of zone currents
  - higher sensitivity to inter-turn faults compared to conventional transformer differential protection
- negative-sequence directional comparison schemes
  - internal fault indicated by a phase angle mismatch between the NSQ of currents entering and leaving the protected zone (transformer), once the current NSQ exceed a minimum threshold
  - improved detection of minor inter-turn transformer faults

Symmetrical components in electrical protection

Transformer protection

- internal fault detection based on equivalent negative-sequence impedances of transformer
  - uses voltage NSQ and current NSQ on both sides of transformer
  - secondary side quantities are referred to primary side
  - internal fault indicated by large difference between negative-sequence impedances of the two sides
- transient events detection based on negative-sequence admittance of transformer
  - uses voltage PSQ and current PSQ on both sides of transformer
  - localization on a specific quadrant of the accumulated positive-sequence admittances indicates the event type, e.g. normal operation, internal fault, external fault or inrush conditions

Symmetrical components in electrical protection

Transformer protection

- inrush restraining algorithm for differential protection based on negative-sequence power
  - negative-sequence power calculated using voltage NSQ of primary and NSQ of differential current
  - transformer energization does not cause a significant negative-sequence power
  - 2^{nd} harmonic restraint disabled upon detection of significant negative-sequence power

- internal/external fault discrimination based on criteria involving symmetrical components
  - internal fault indicated by the increase above a threshold of I_2/I_1 ratio of differential current
  - internal fault indicated by the increase above a threshold of I_2/I_1 ratio of primary current

Symmetrical components in electrical protection

Protection of electrical machines

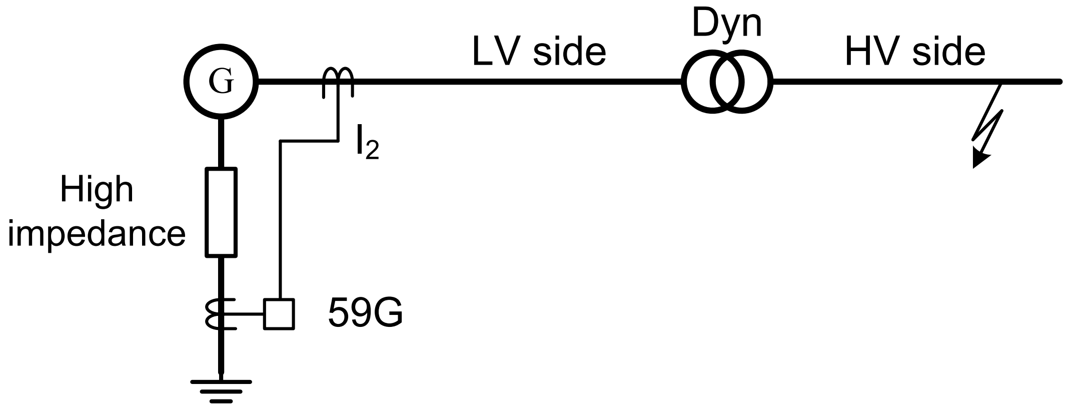
- open-phase and unbalance protection
  - overcurrent elements operating on current NSQ
  - overvoltage elements operating on voltage NSQ
  - directional power elements operating on negative-sequence power
  - elements tripping on a significant I_2/I_1 ratio or significant V_2/V_1 ratio
- stator-rotor current differential elements for inter-turn fault protection of synchronous generators
  - based on ampere-turn balance between the fields created by the NSQ of stator current and by the rotor double-frequency current

Symmetrical components in electrical protection

Protection of electrical machines

- improvement of a generator ground fault protection using current NSQ
  - stator ground faults detected by ground overvoltage element (59G)
  - 59G could trip for ground faults on HV side due to zero-sequence voltage coupling
  - miss-operation avoided by delaying operation of 59G – not optimal for generator faults

  - improvement: accelerated 59G operation in the absence of a significant current NSQ at generator terminals
  - significant current NSQ generated by faults on HV side, but not for generator internal faults



Symmetrical components in electrical protection

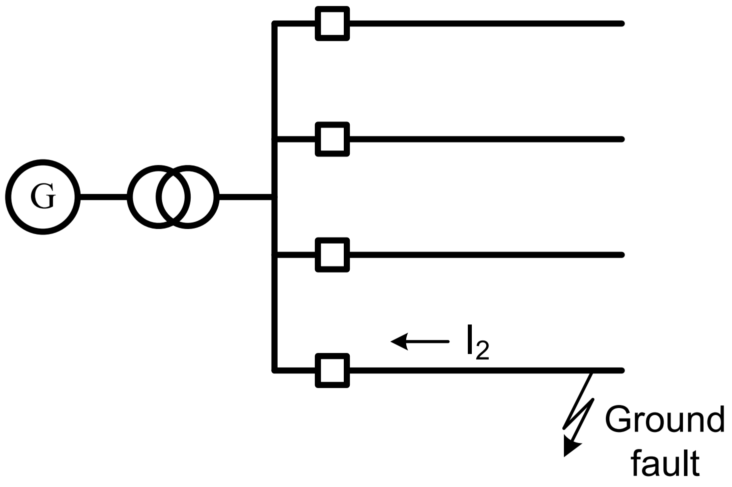
Protection of distribution networks

- ground fault protection
  - overcurrent elements operating on current ZSQ
  - overvoltage elements operating on voltage ZSQ
  - directional elements operating on current ZSQ and voltage ZSQ
  - zero-sequence wattmetric protection
- phase fault protection
  - overcurrent elements operating on current NSQ
  - overvoltage elements operating on voltage NSQ

Symmetrical components in electrical protection

Protection of distribution networks

- ground fault protection based on NSQ in ungrounded systems
  - current NSQ larger than current ZSQ in faulty feeders
  - current NSQ practically non-existent in healthy feeders
  - ground faults detected by zero-sequence overvoltage relays placed on each feeder, with adaptive (accelerated) operation upon detection of current NSQ



- fault section identification (ground fault) in distribution feeders based on comparison of the differential ZSQ current with the capacitive current expected on protected section section

Symmetrical components in electrical protection

Microgrid protection

- microgrids (active distribution networks) are more challenging for protection compared to traditional distribution network due to:
    - presence of distributed generators (characterized by intermittent generation)
    - directional power flow (requirement of directional elements)
    - variability of short-circuit currents (grid-connected mode vs. islanded mode)
    - relatively reduced short-circuit power (mal-operation of overcurrent relays)
- some authors proposed utilization of protection methods based on symmetrical components to mitigate the challenges of microgrid protection

Symmetrical components in electrical protection

Microgrid protection

- overcurrent protection based on symmetrical components
    - phase faults indicated by current NSQ
    - ground faults indicated by current ZSQ
- directional protection based on symmetrical components
    - positive-sequence directional elements
    - negative-sequence directional elements
- communication-based directional schemes using logic discrimination for accelerated tripping

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Conclusion

- a literature review of the most interesting technical papers discussing the use of symmetrical components in protection relaying has been realized
- the theoretical background of the method of symmetrical components and the derivation of these quantities from phase-domain counterparts have also been presented
- the literature study indicates a very high relevance of symmetrical components in electrical protection, which will continue, most probably, in the future
- modern protection relays and the method of symmetrical components could allow the development of new and more complex protection algorithms

Thank you!