Sequence Component Applications in Protective Relays – Advantages, Limitations, and Solutions

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Symmetrical Components Are 100 Years Old

Charles Legeyt Fortescue

Presented at the 34th Annual Convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 28, 1918.

METHOD OF SYMMETRICAL CO-ORDINATES APPLIED TO THE SOLUTION OF POLYPHASE NETWORKS

BY C. L. FORTESCUE

Abstract of Paper

In the introduction a general discussion of unsymmetrical systems of co-planar vectors leads to the conclusion that they may be represented by symmetrical systems of the same number of vectors, the number of symmetrical systems required to define the given system being equal to its degrees of freedom. A few trigonometrical theorems which are to be used in the paper are called to mind. The paper is subdivided into three parts, an abstract of which follows. It is recommended that only that part of Part I up to formula (33) and the portion dealing with star-delta transformations be read before proceeding with Part II.

Part I deals with the resolution of unsymmetrical groups of numbers into symmetrical groups. These numbers may represent rotating vectors of systems of operators. A new operator termed the sequence operator is introduced which simplifies the manipulation. Formulas are derived for three-phase circuits. Star-delta transformations for symmetrical co-ordinates are given and expressions for power deduced. A short discussion of harmonics in three-phase systems is given.

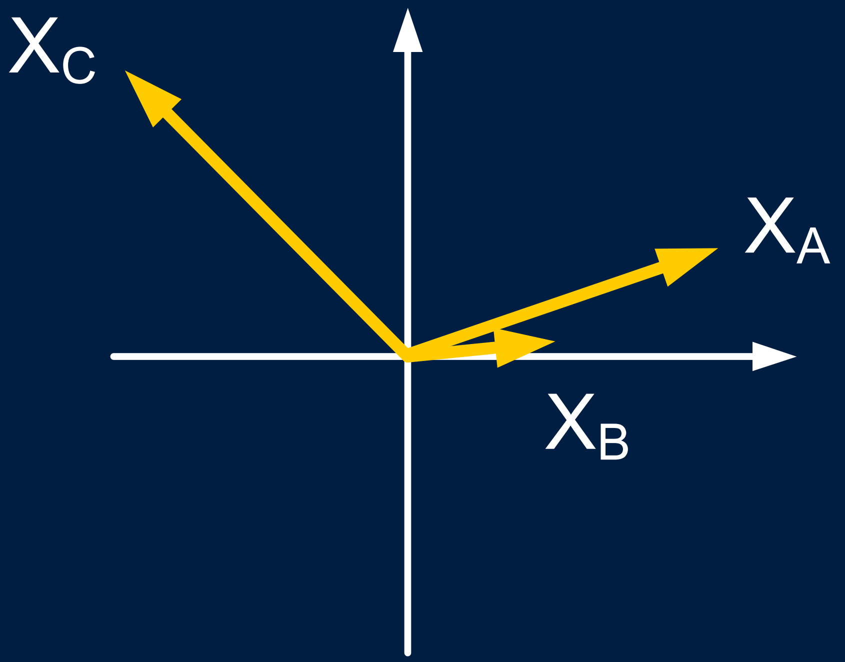
Part II deals with the practical application of this method to symmetrical rotating machines operating on unsymmetrical circuits. General formulas are derived and such special cases, as the single-phase induction motor, synchronous motor-generator, phase converters of various types, are discussed.

Introduction

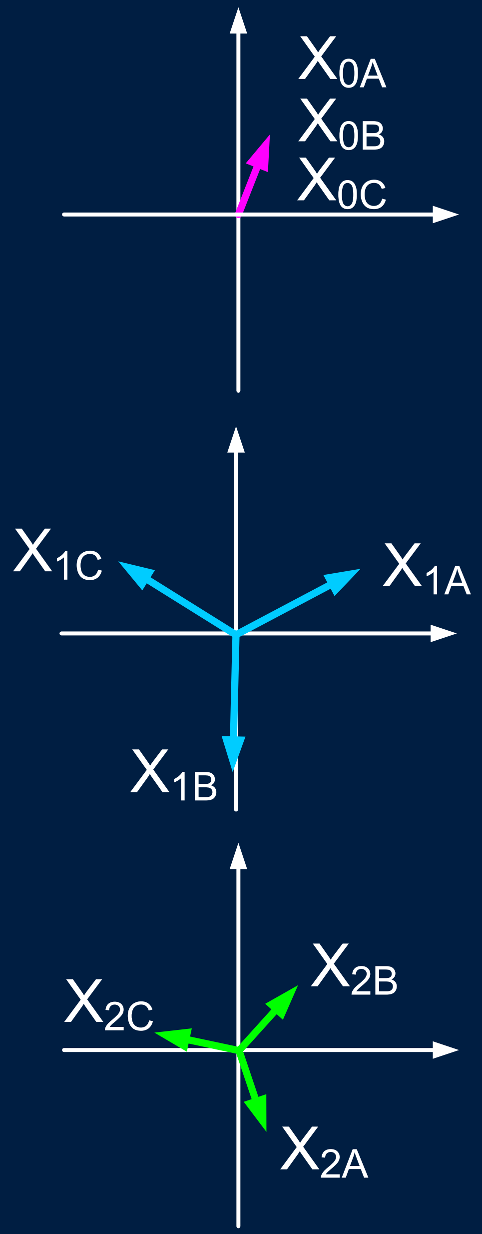
IN THE latter part of 1913 the writer had occasion to investigate mathematically the operation of induction motors under unbalanced conditions. The work was first carried out, having particularly in mind the determination of the operating characteristics of phase converters which may be considered as a particular case of unbalanced motor operation, but the scope of the subject broadened out very quickly and the writer undertook this paper in the belief that the subject would be of interest to many.

The most striking thing about the results obtained was their symmetry; the solution always reduced to the sum of two or more symmetrical solutions. The writer was then led to inquire if there were no general principles by which the solution of unbalanced polyphase systems could be reduced to the solu-

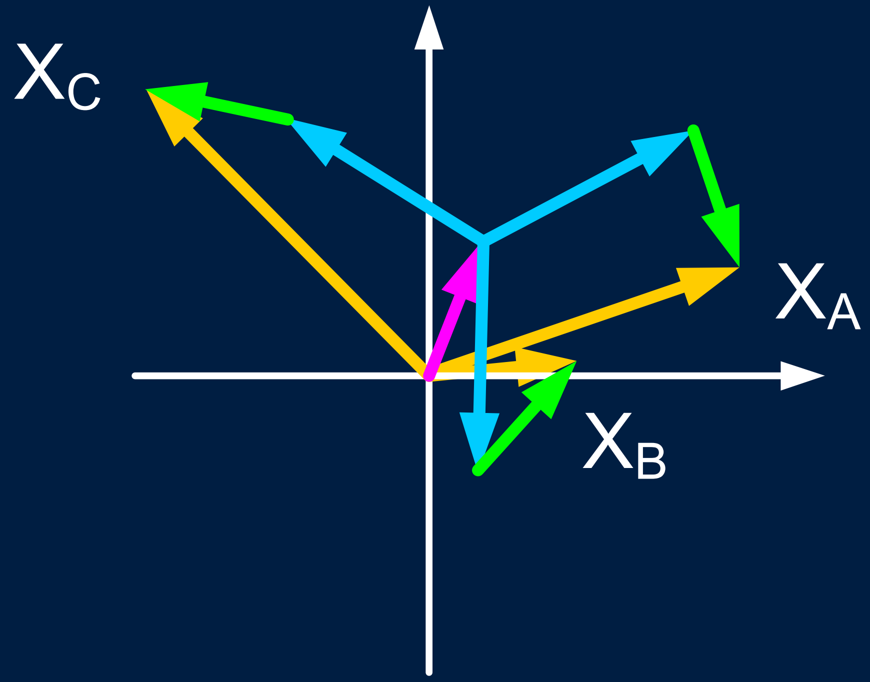
Sequence Components Transformation



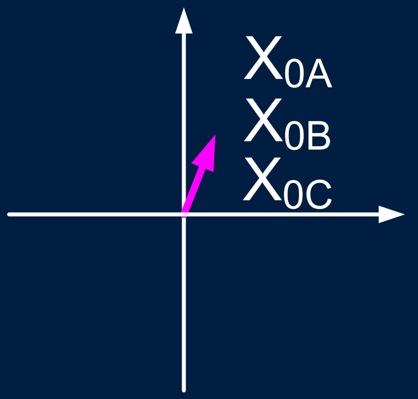
$$\begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix}$$

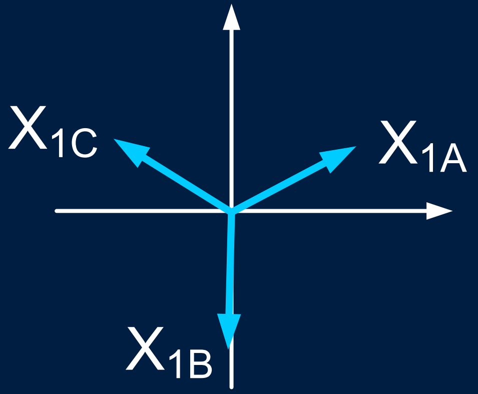


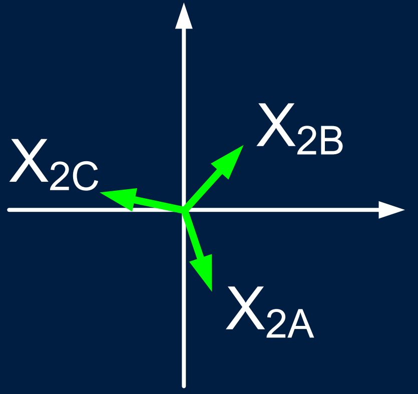
Sequence Components Transformation



$$\begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix}$$

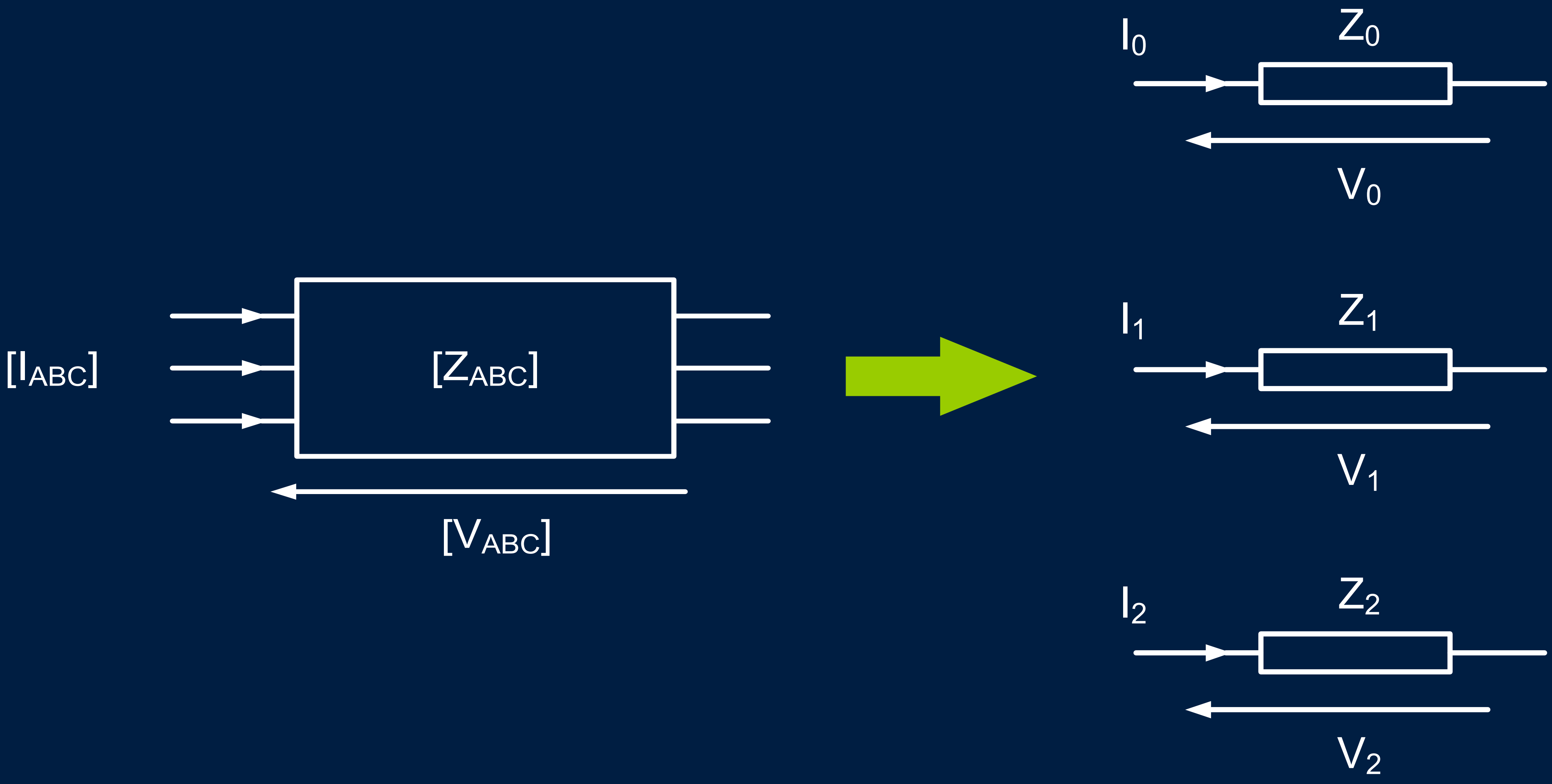






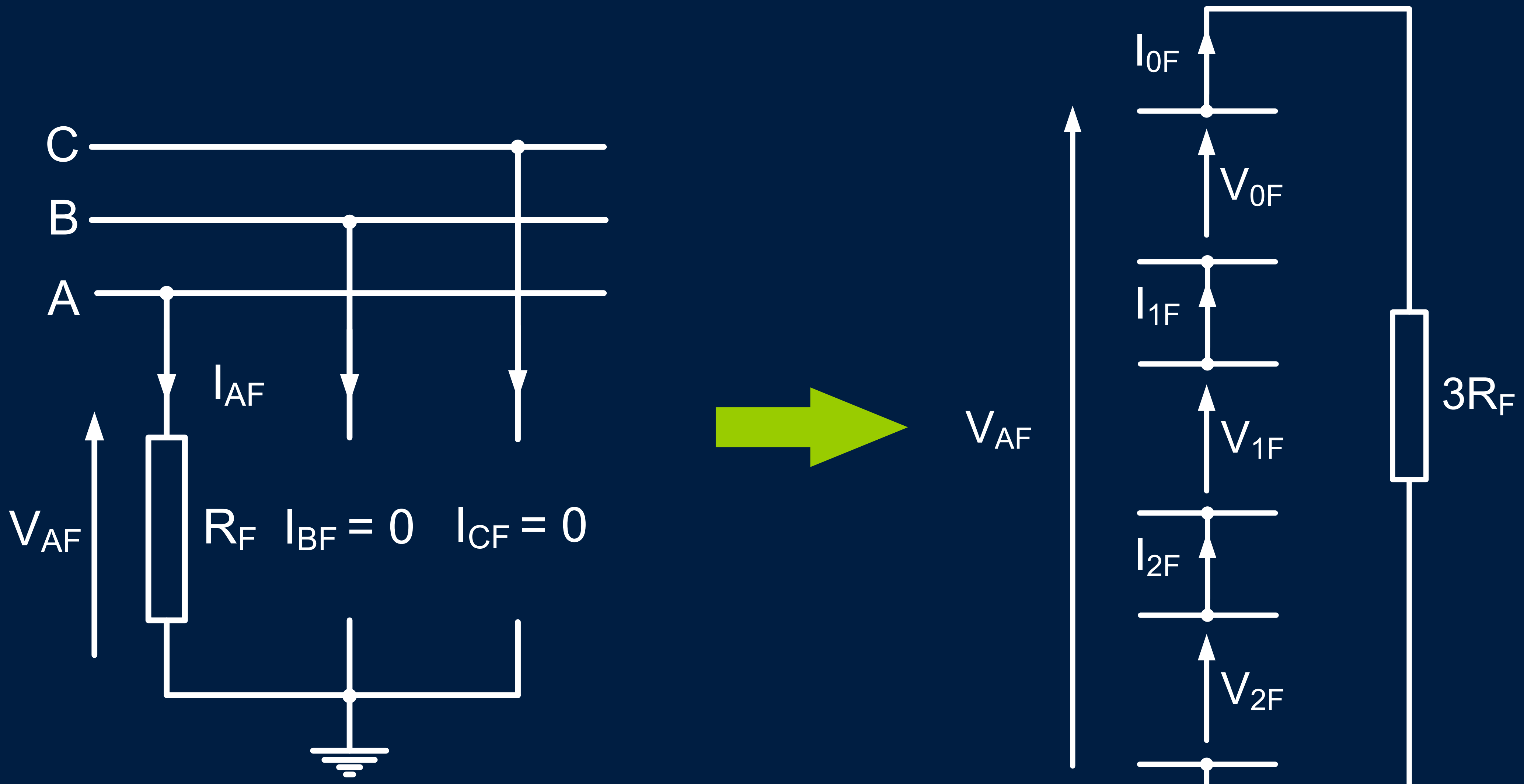
Solving Unbalanced Three-Phase Networks

Represent Each Element With a Sequence Model



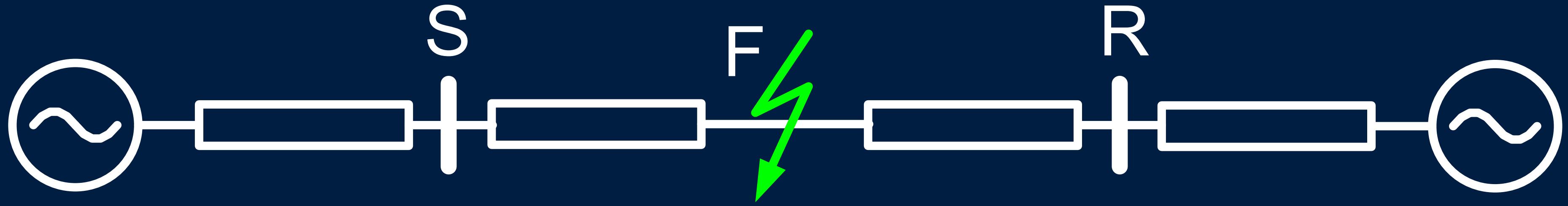
Solving Unbalanced Three-Phase Networks

Connect Sequence Networks According to Unbalance



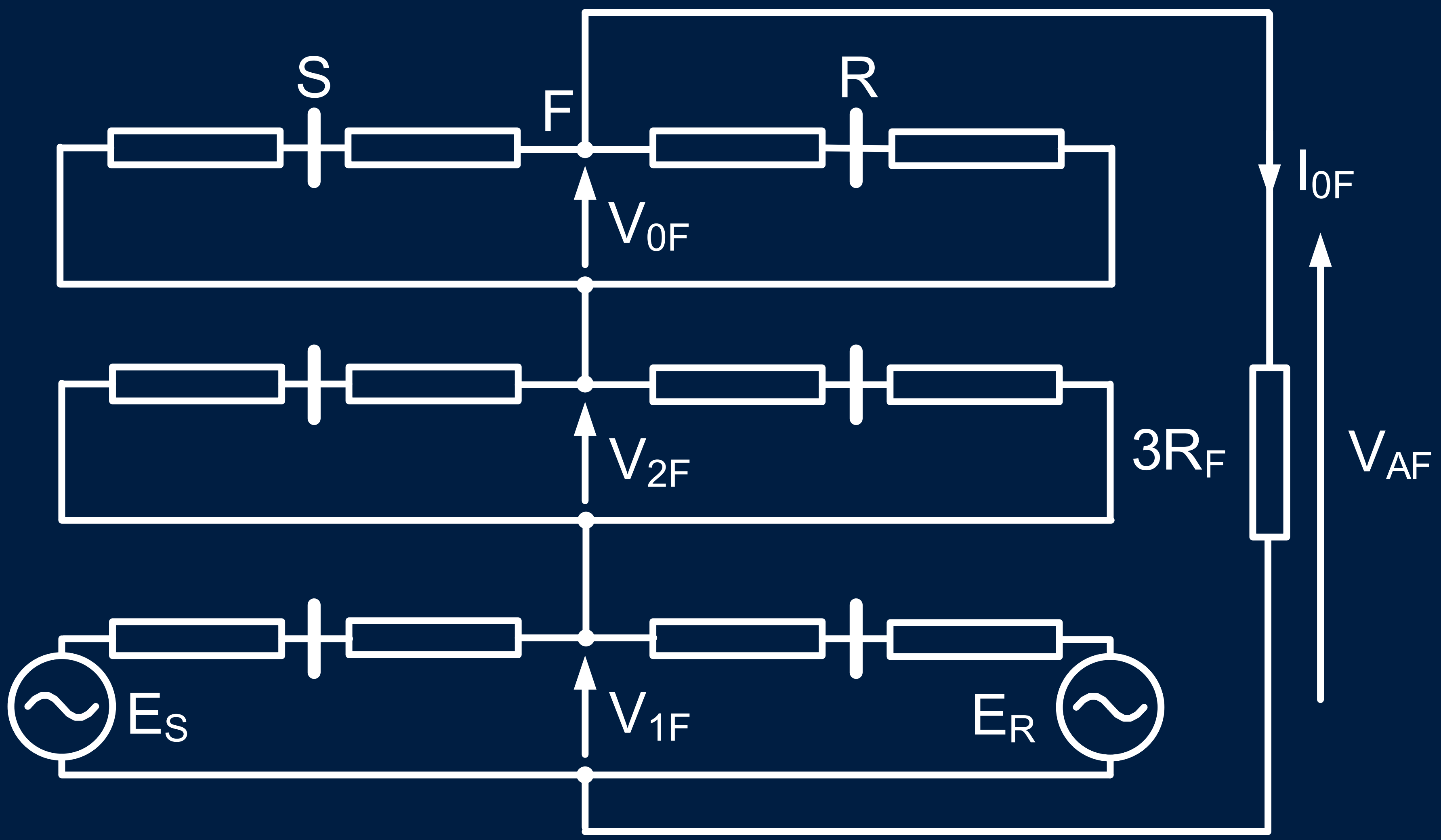
Solving Unbalanced Three-Phase Networks

Solve a Single-Phase Network



Solving Unbalanced Three-Phase Networks

Solve a Single-Phase Network

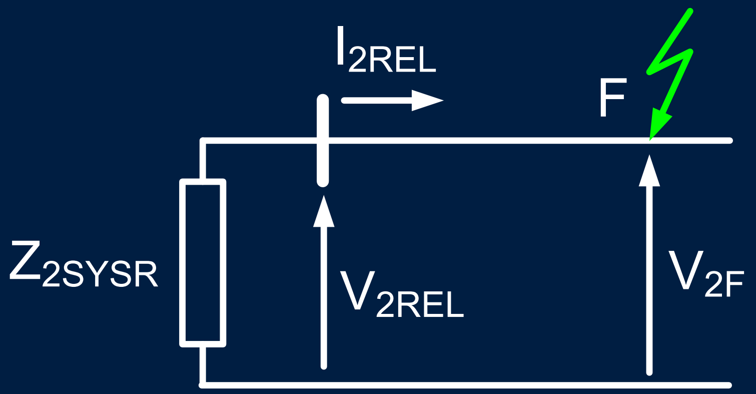


Protection Applications of Sequence Components

- Negative-sequence directional
- Zero-sequence directional
- Negative-sequence differential
- Zero-sequence differential
- Restricted earth fault
- Fault type identification
- System unbalance protection
- Disturbance detectors
- LOP and CT failure detection
- Distance element polarizing
- Fault locating
- Stator-field unbalance

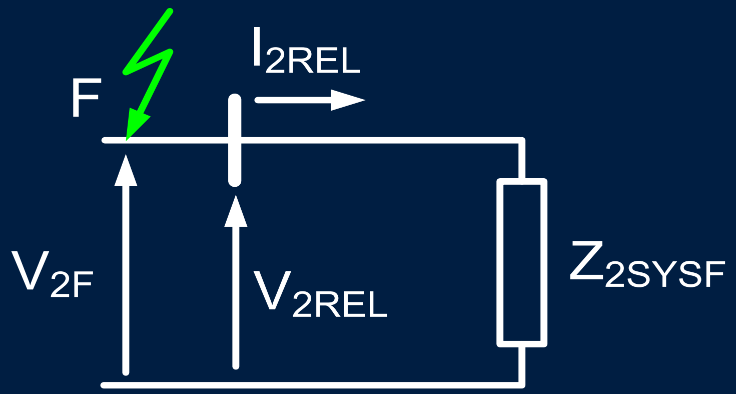
Directional Elements

Forward Fault



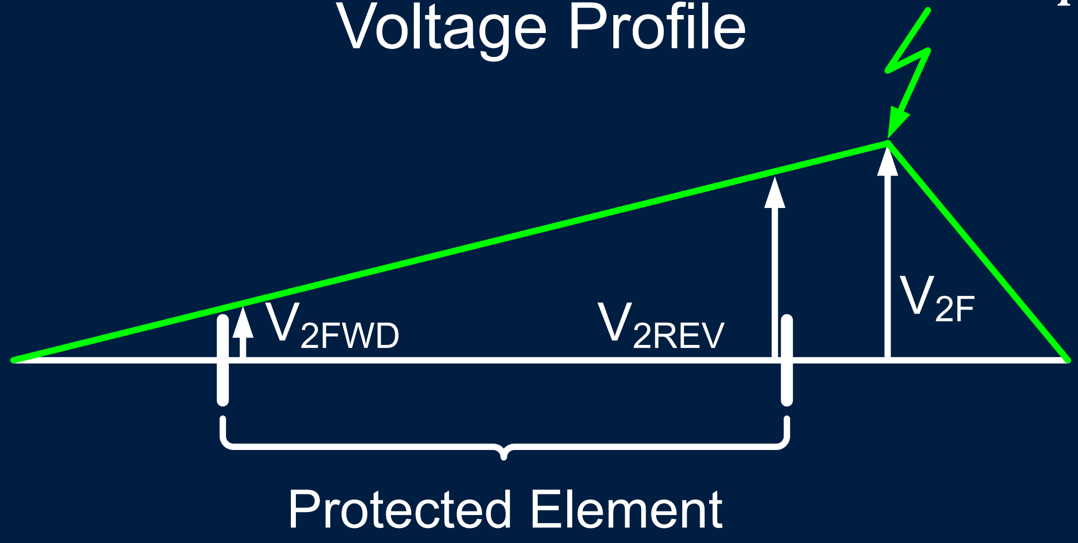
$$Z_2 = \frac{V_{2REL}}{I_{2REL}} = -Z_{2SYSR}$$

Reverse Fault



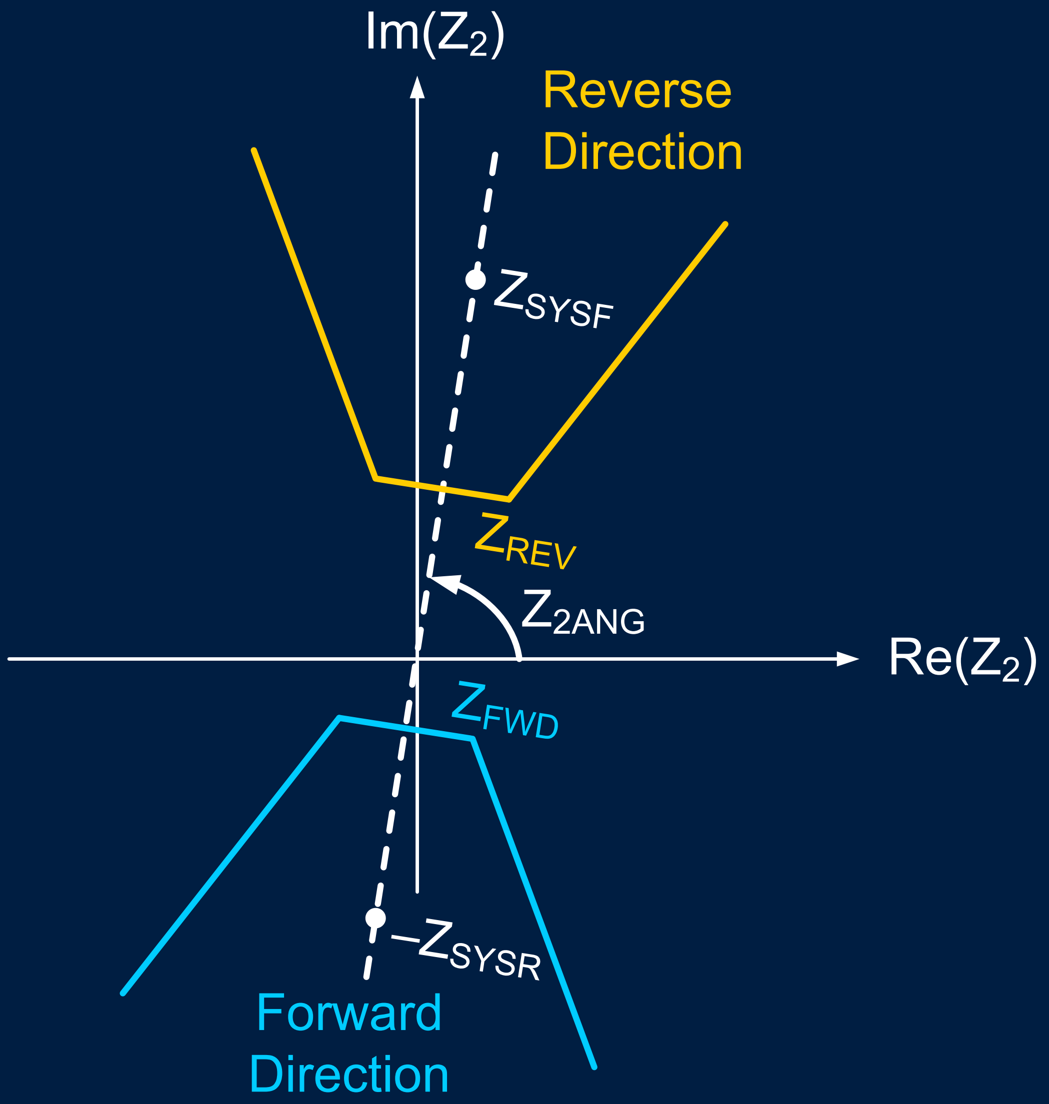
$$Z_2 = \frac{V_{2REL}}{I_{2REL}} = +Z_{2SYSF}$$

Voltage Profile



Directional Elements

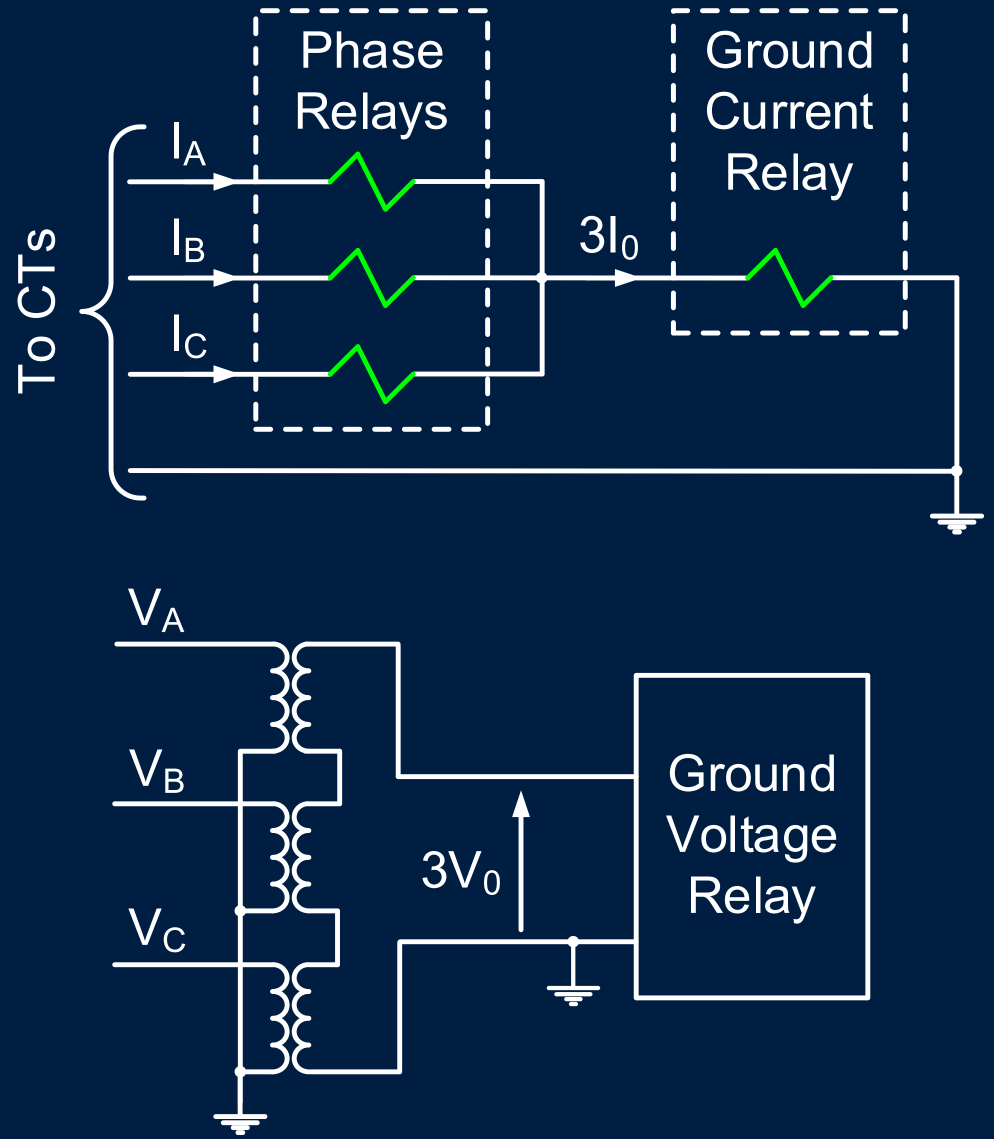
Impedance Plane Implementation (32Q, 32G)



- Sensitivity
- Speed of operation
- Simple settings
- Improved security through limited comparator angle

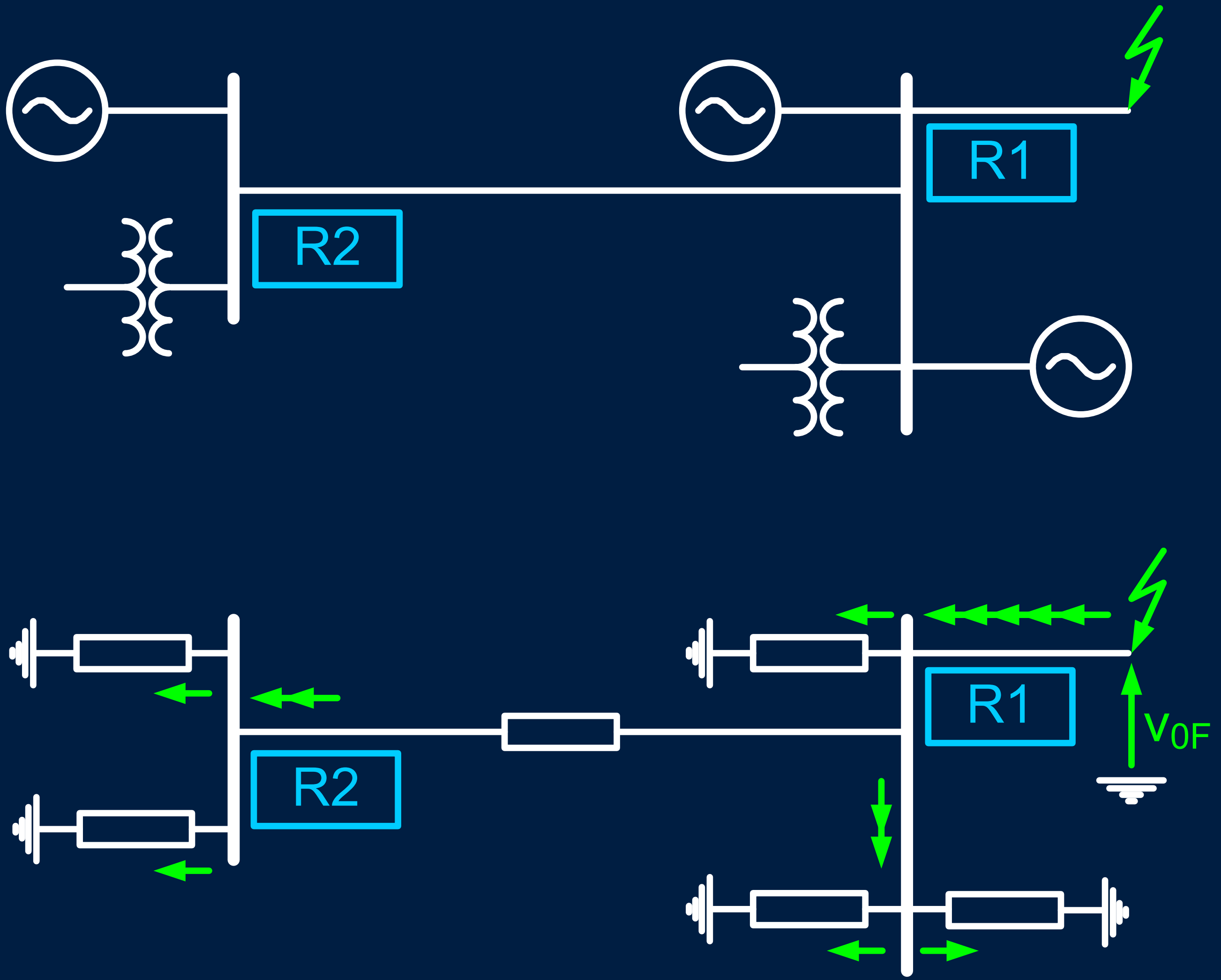
Directional Elements

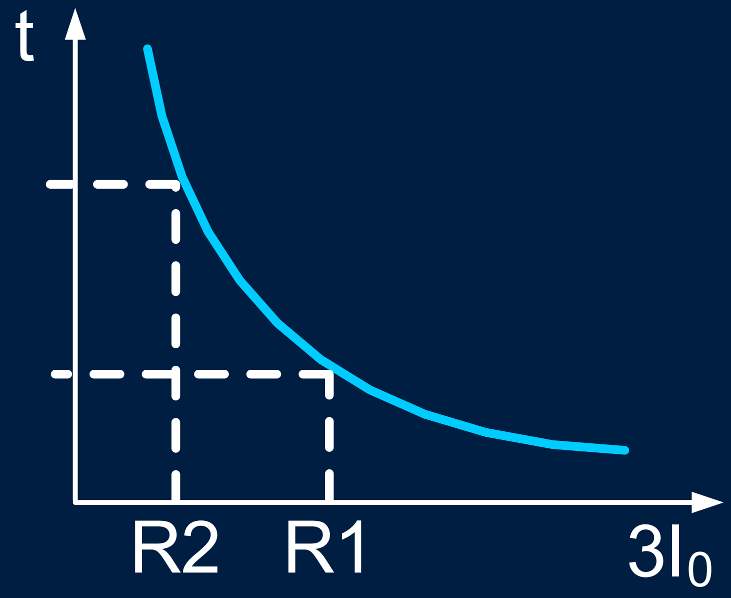
Zero-Sequence or Negative-Sequence?



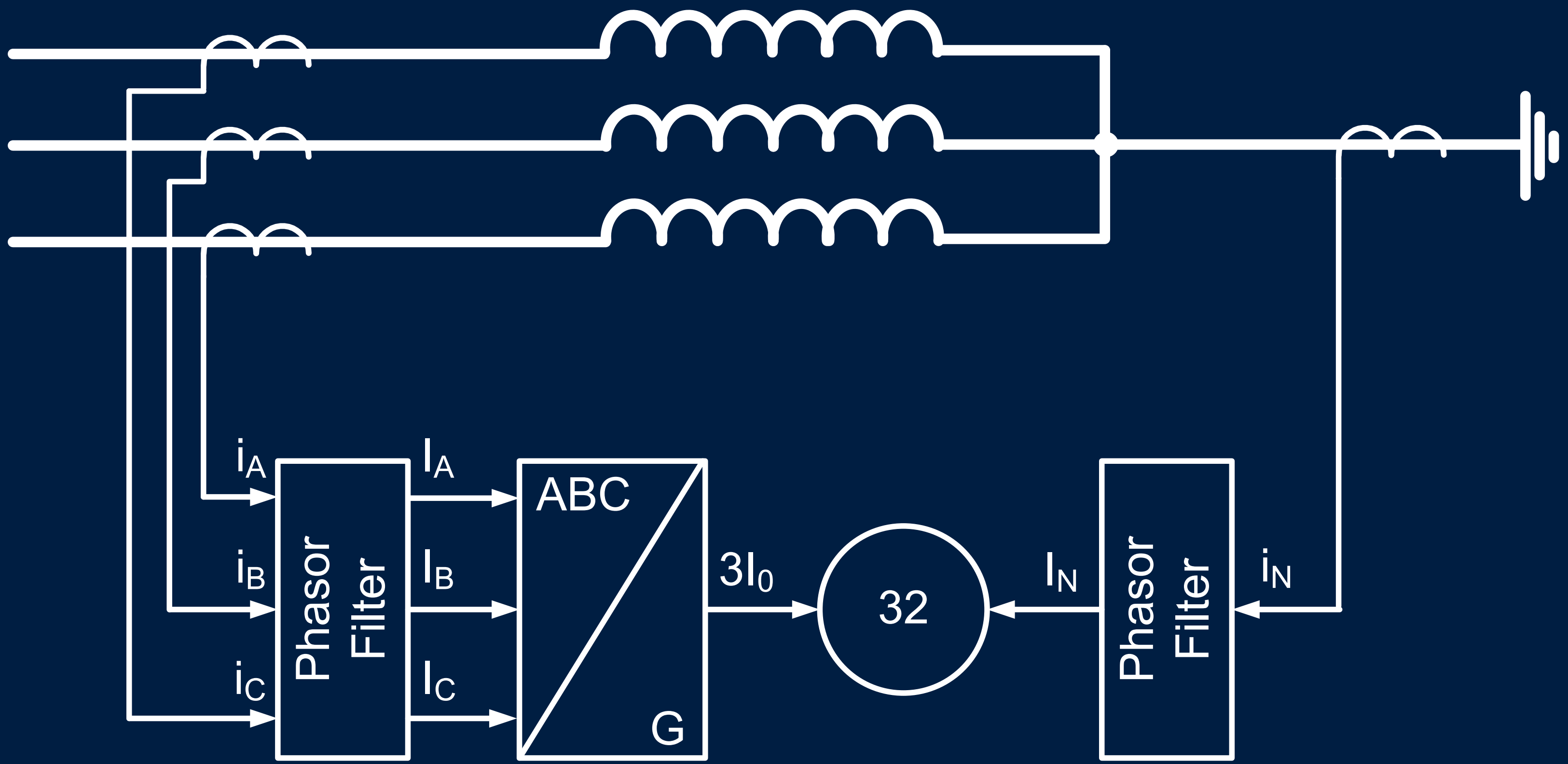
- Analog relays pay a price in cost, size, and reliability when obtaining negative-sequence
- Today, with μP-based relays, application drives the selection
- Effect of mutual coupling favors negative-sequence
- Nonstandard sources favor zero-sequence

Ground Fault Protection





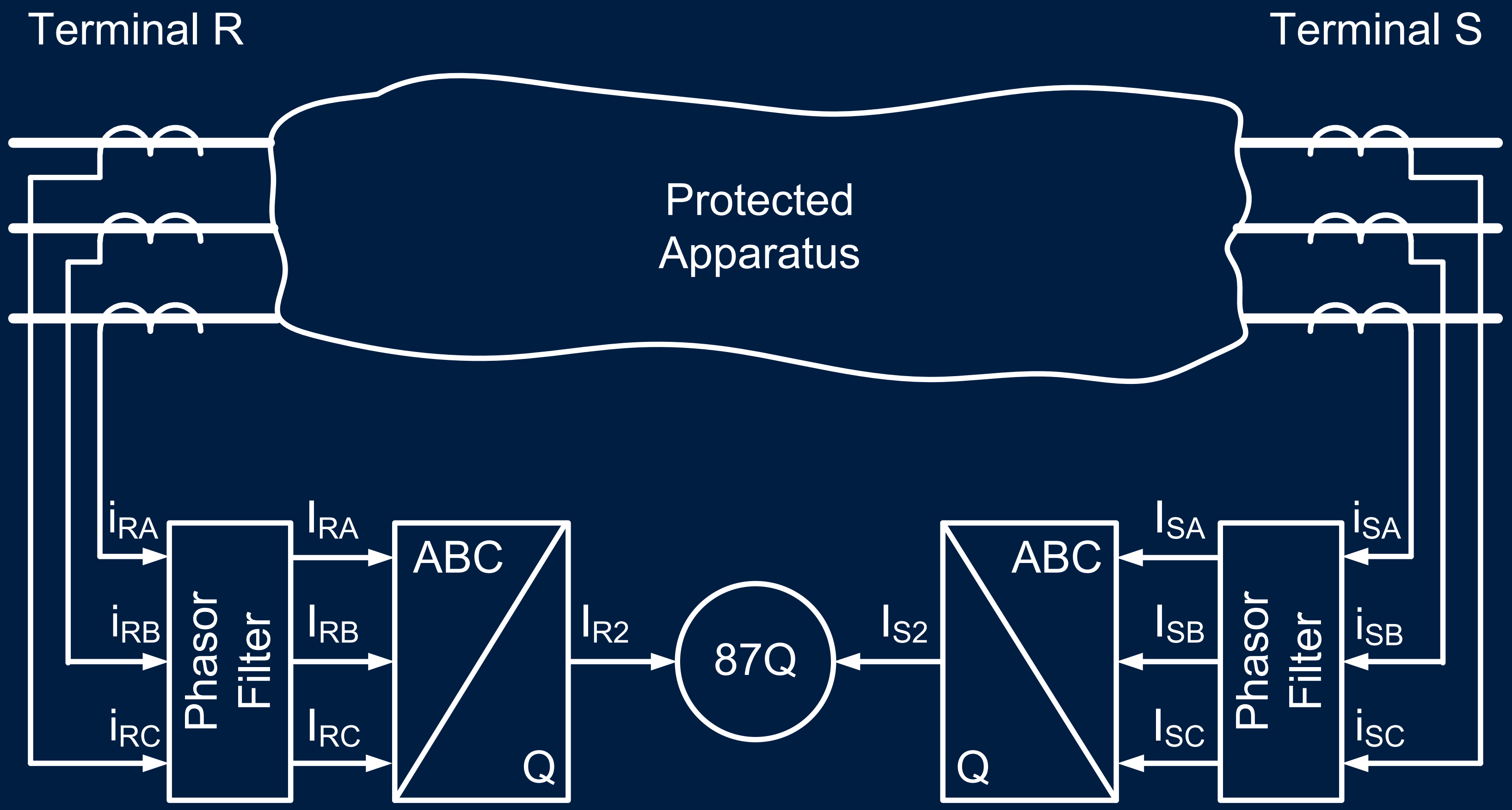
Restricted Earth Fault



$$I_{OP} = I_N$$

$$I_{POL} = 3I_0$$

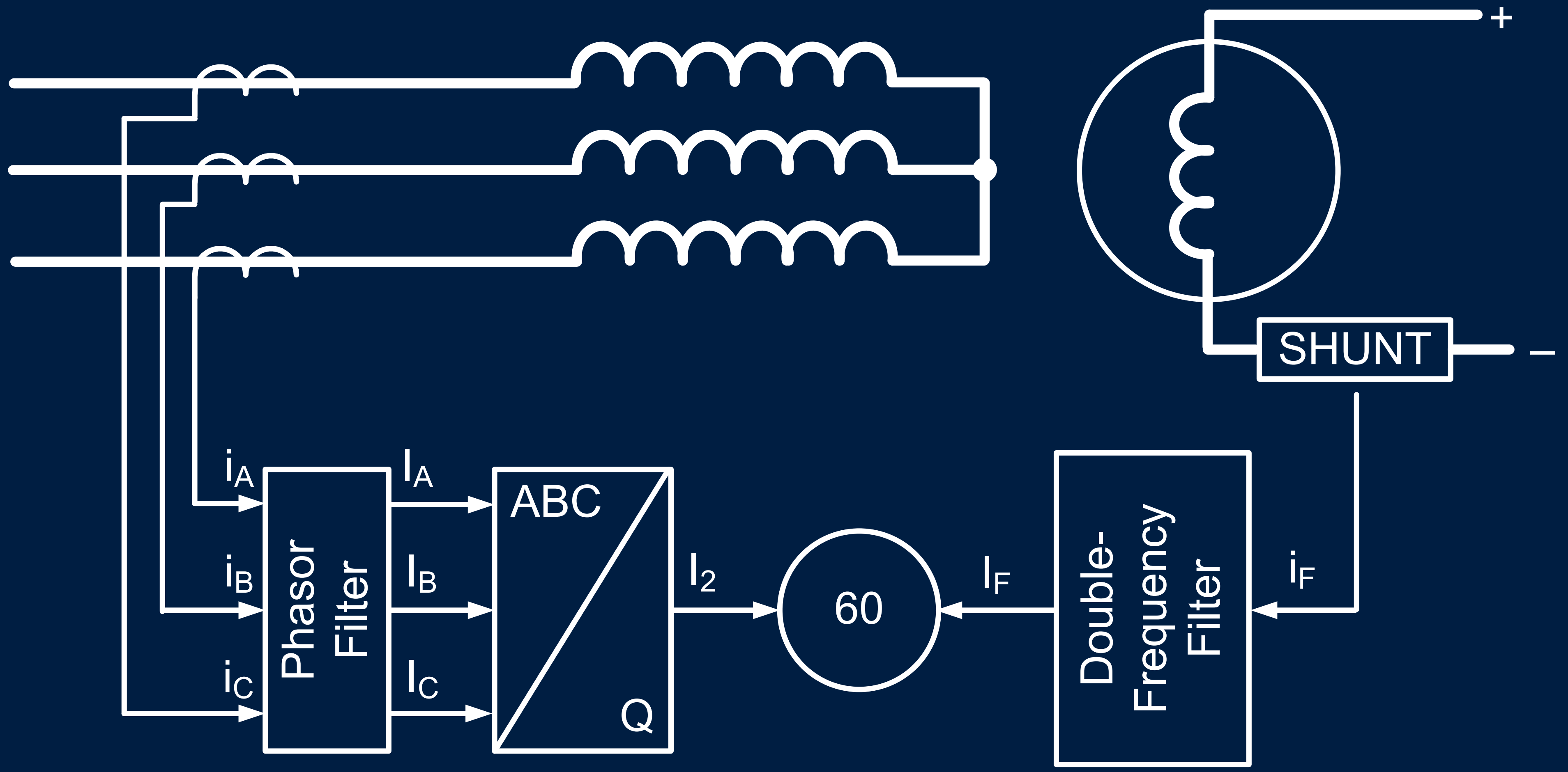
Negative-Sequence Differential



$$I_{OP} = |\Sigma I_2|$$

$$I_{RT} = \Sigma |I_2|$$

Stator-Field Unbalance

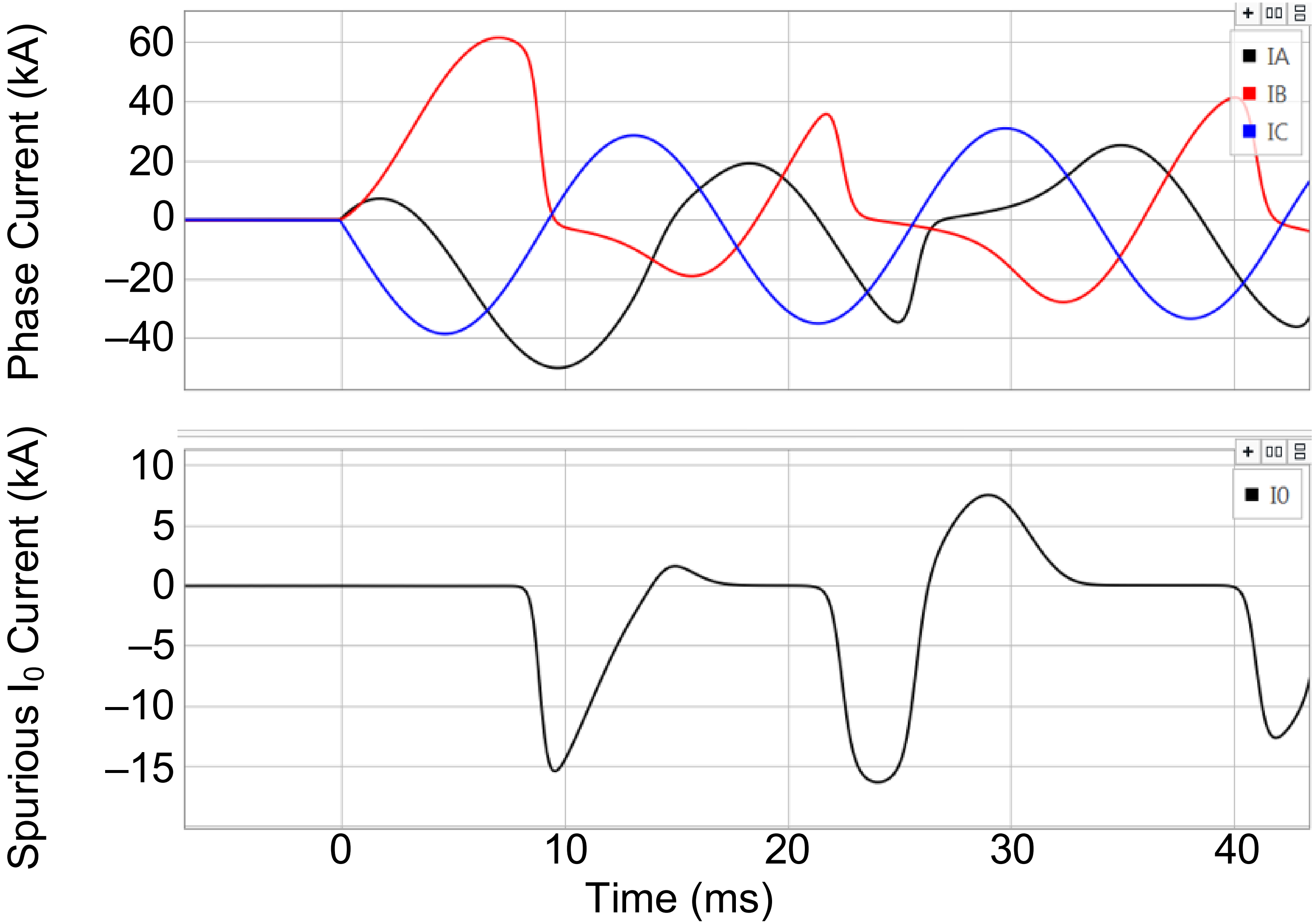


Many Events Drive Sequence Components, Not Only Faults

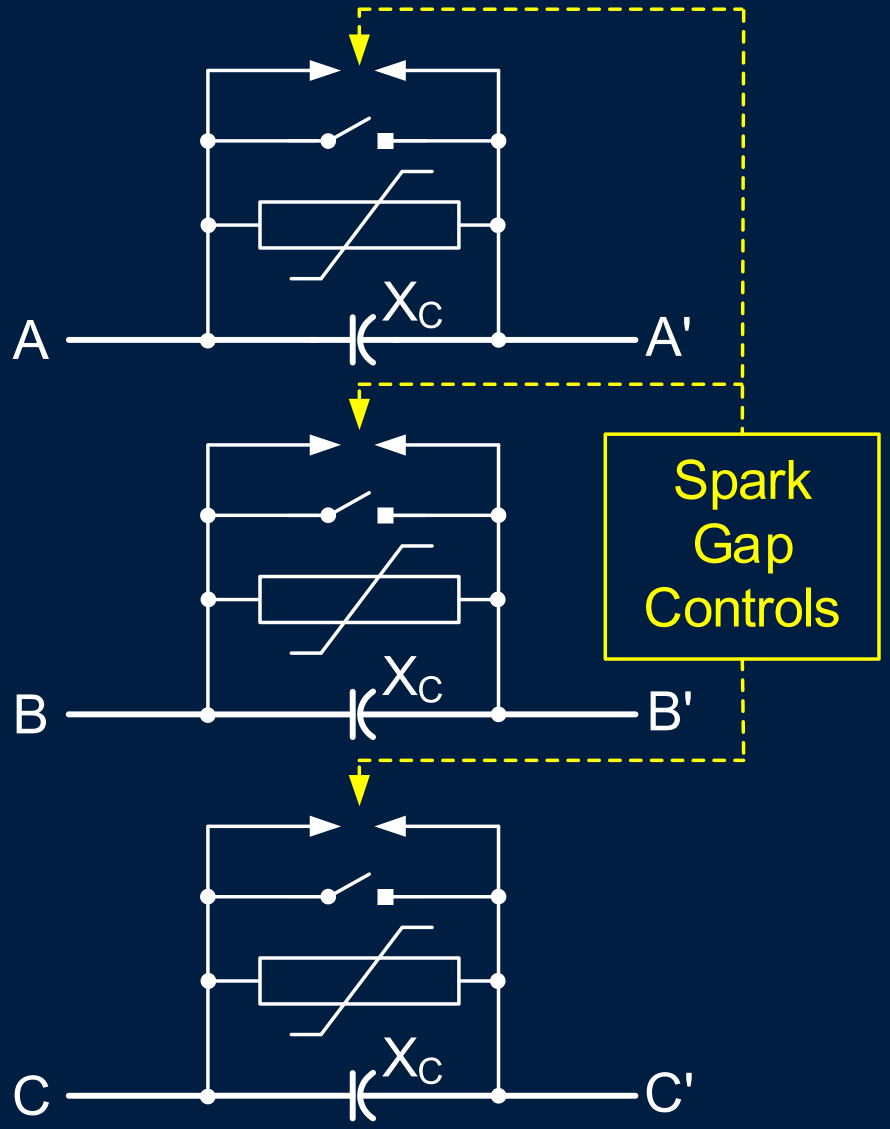
- System unbalance
- Open pole
- Instrument transformer errors
  - CT ratio errors and saturation
  - VT ratio errors, coupled signals, CCVT transients
- Breaker pole scatter
- Filter transients
- Asymmetrical bypass of series capacitors

CT Saturation

Three-Phase Fault



Asymmetrical Bypass of Series Capacitors
(AG Fault)



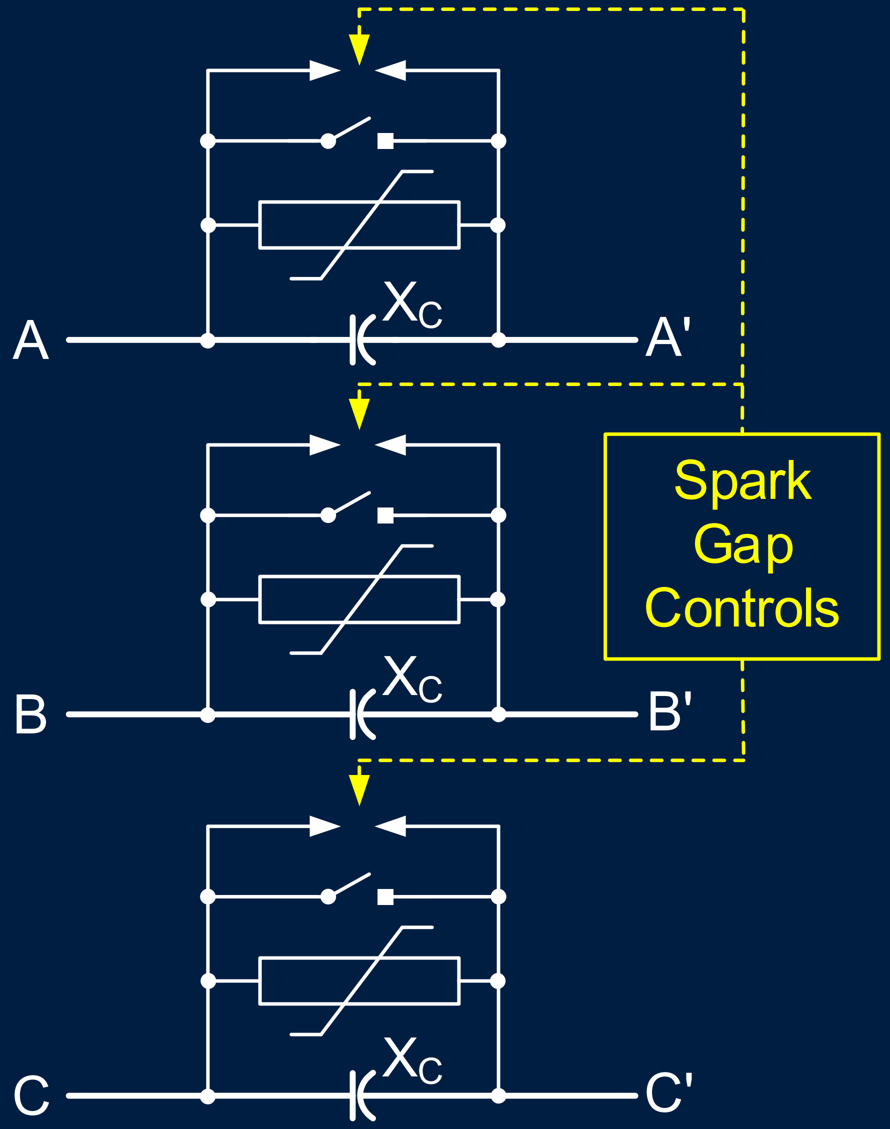
Phase Impedances

$$-jX_C \begin{bmatrix} 1 \rightarrow 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Sequence Impedances

$$-j\frac{X_C}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

Asymmetrical Bypass of Series Capacitors
(BC or BCG Fault)



Phase Impedances

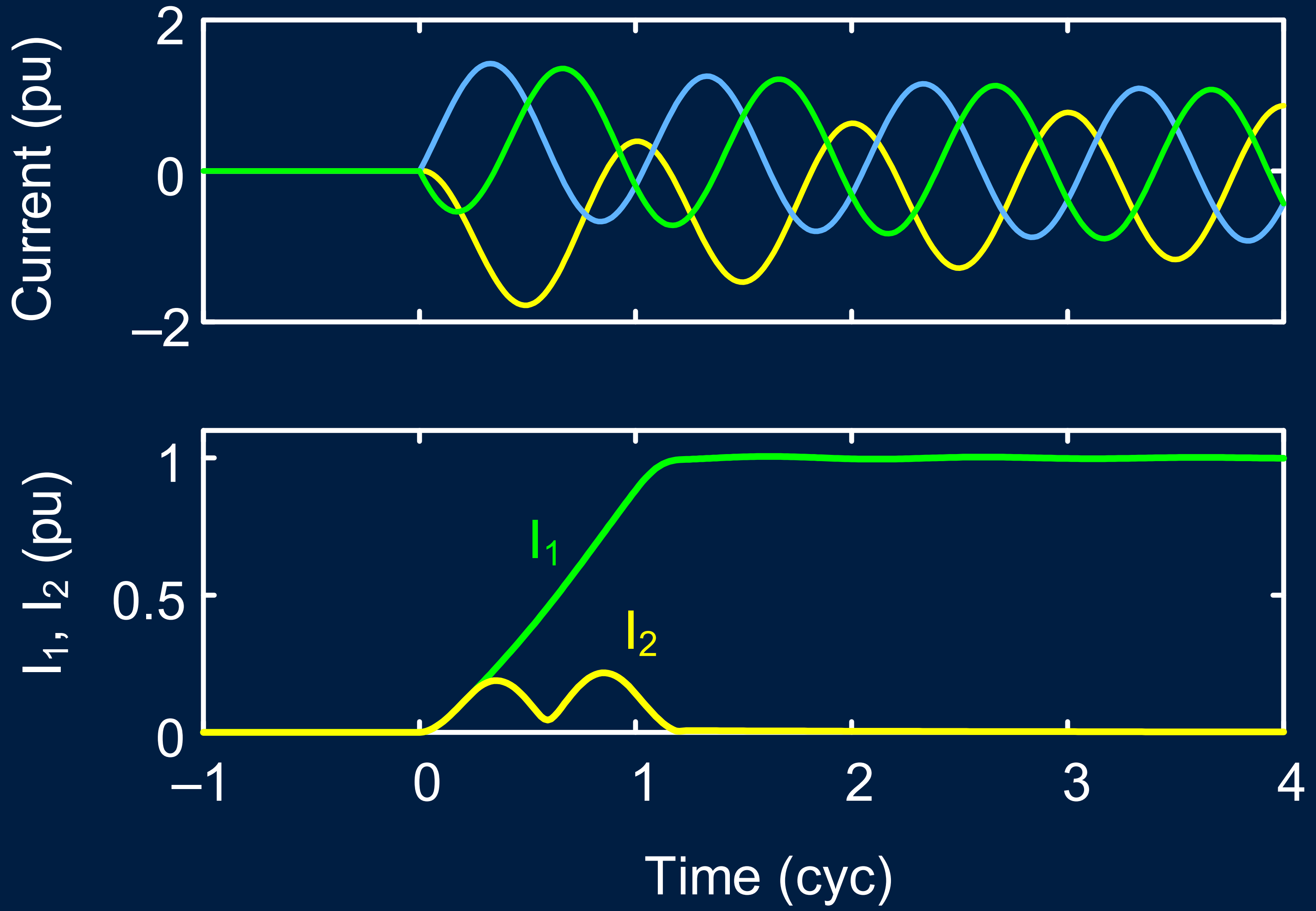
$$-jX_C\begin{bmatrix}1 & 0 & 0\\ 0 & 1\rightarrow 0 & 0\\ 0 & 0 & 1\rightarrow 0\end{bmatrix}$$

Sequence Impedances

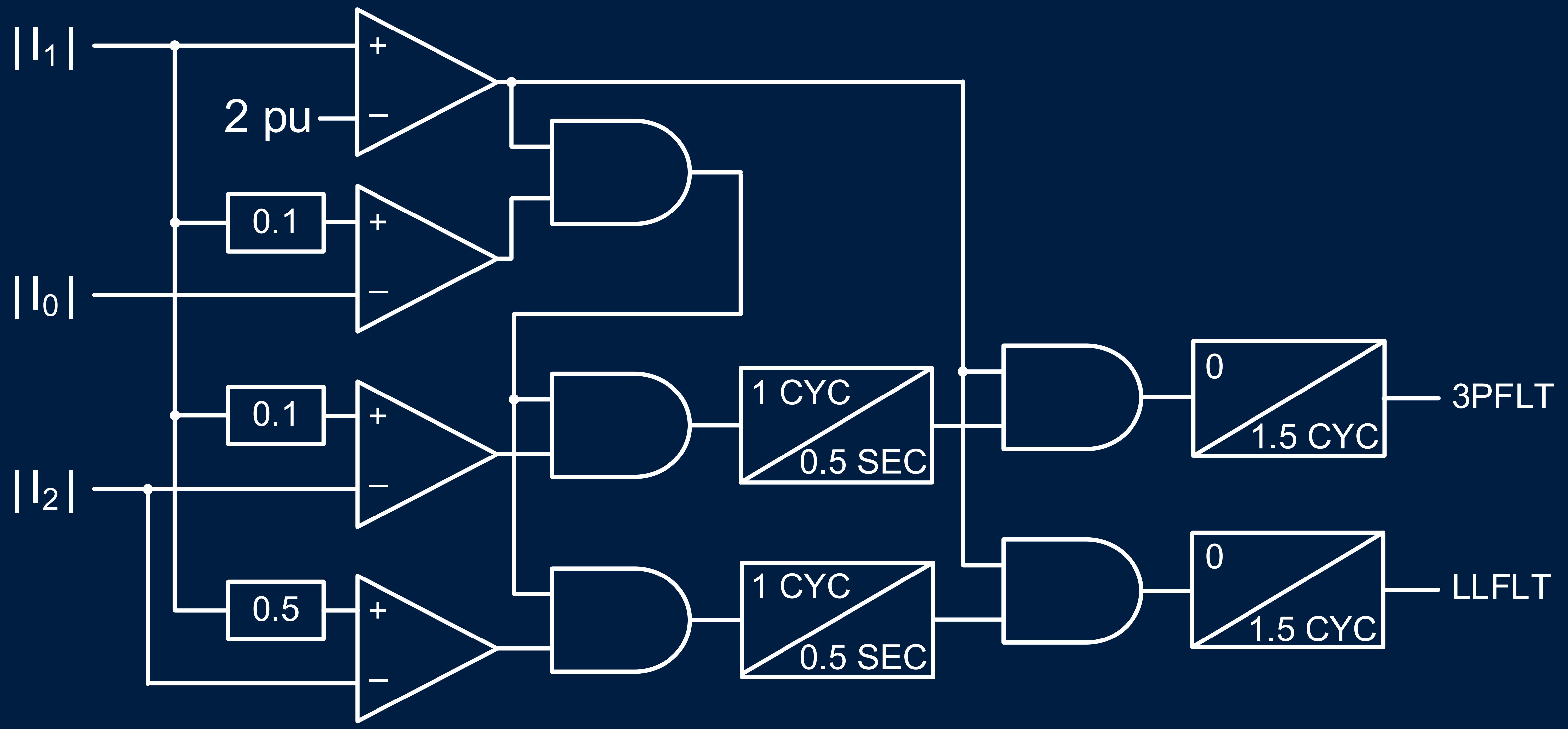
$$-j\frac{X_C}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix}$$

Filter Transients

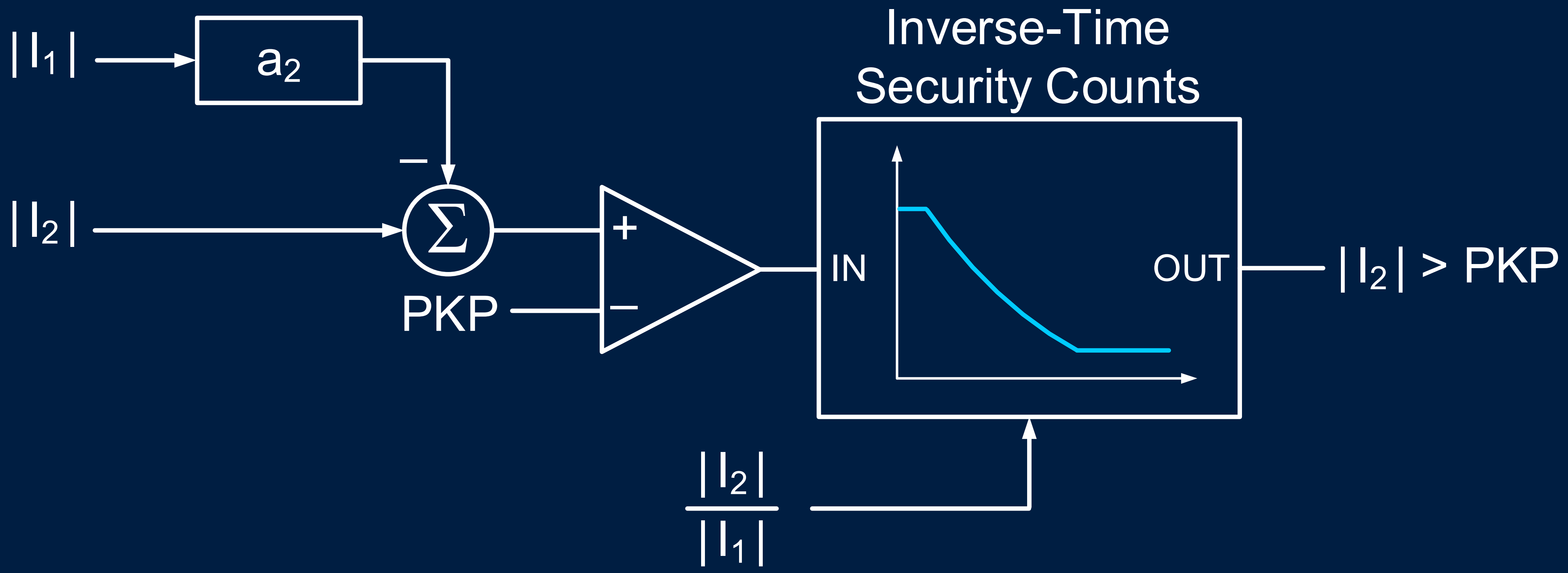
Three-Phase Balanced Fault



Securing Sequence Elements for CT Errors



Securing Sequence Elements for Small System Unbalances and Errors



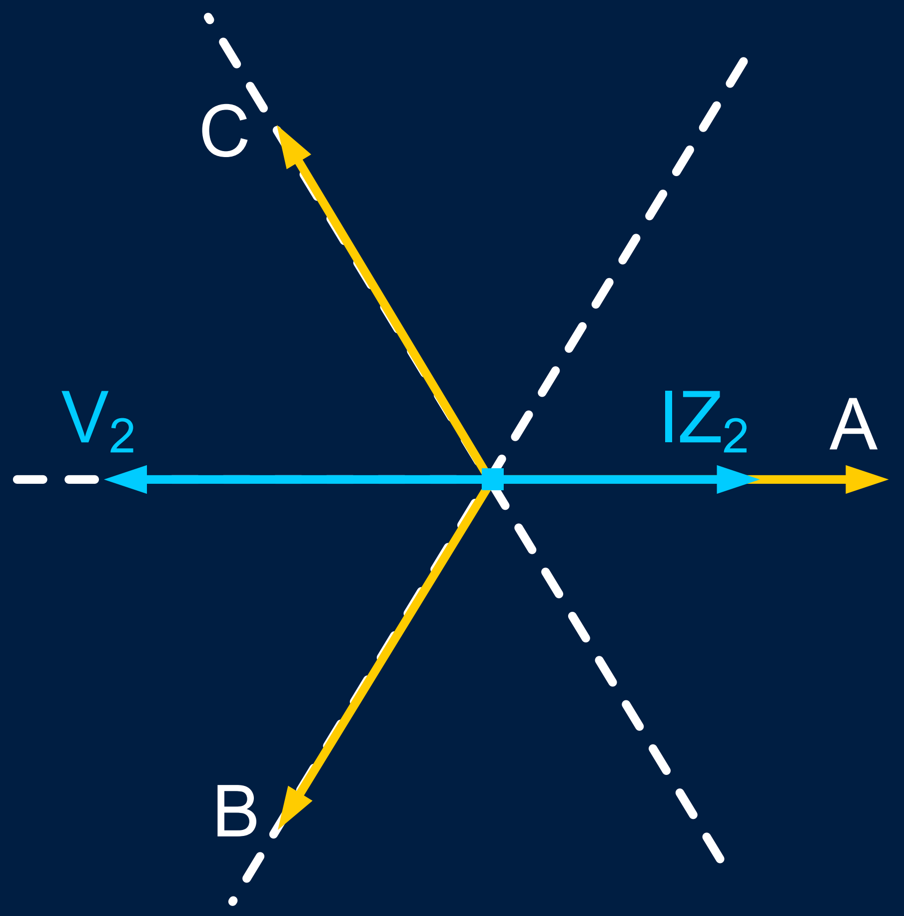
Using Right Schemes for a Protection Job

Cross-Country Fault Example

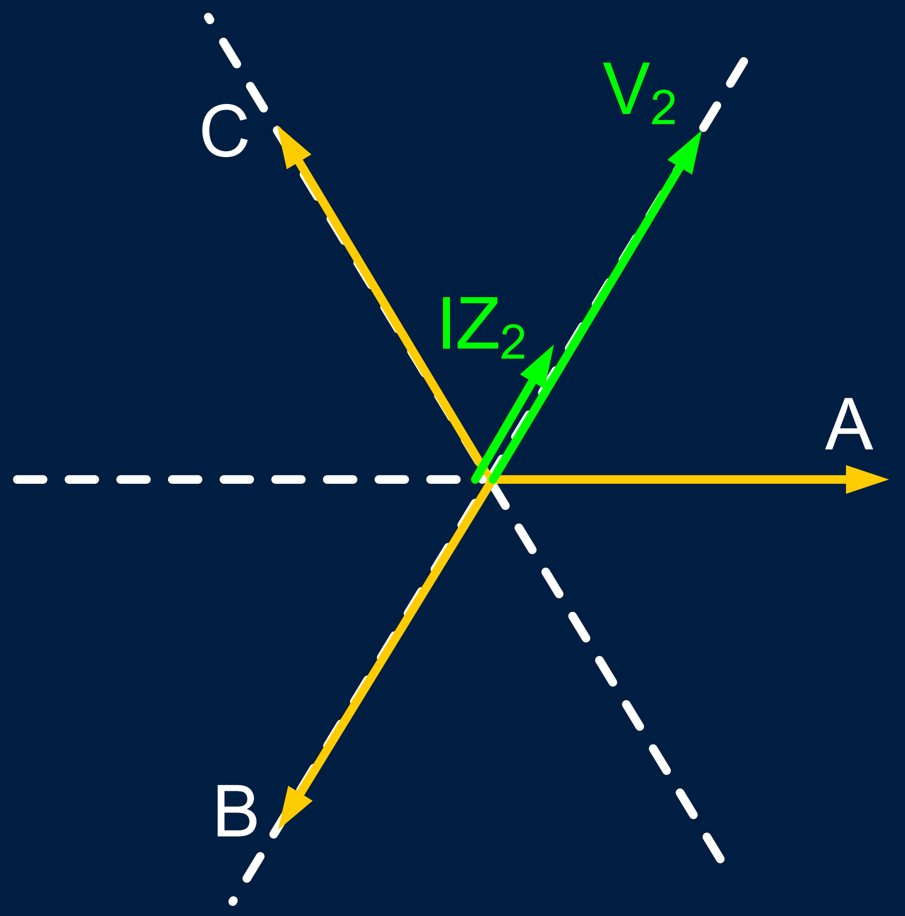
- R2 must see the internal fault
- R2 must identify the faulted phase
- Can we count on 32Q, 32G, and fault type logic in R2?

Cross-Country Fault Analysis

Only Forward AG Fault Present

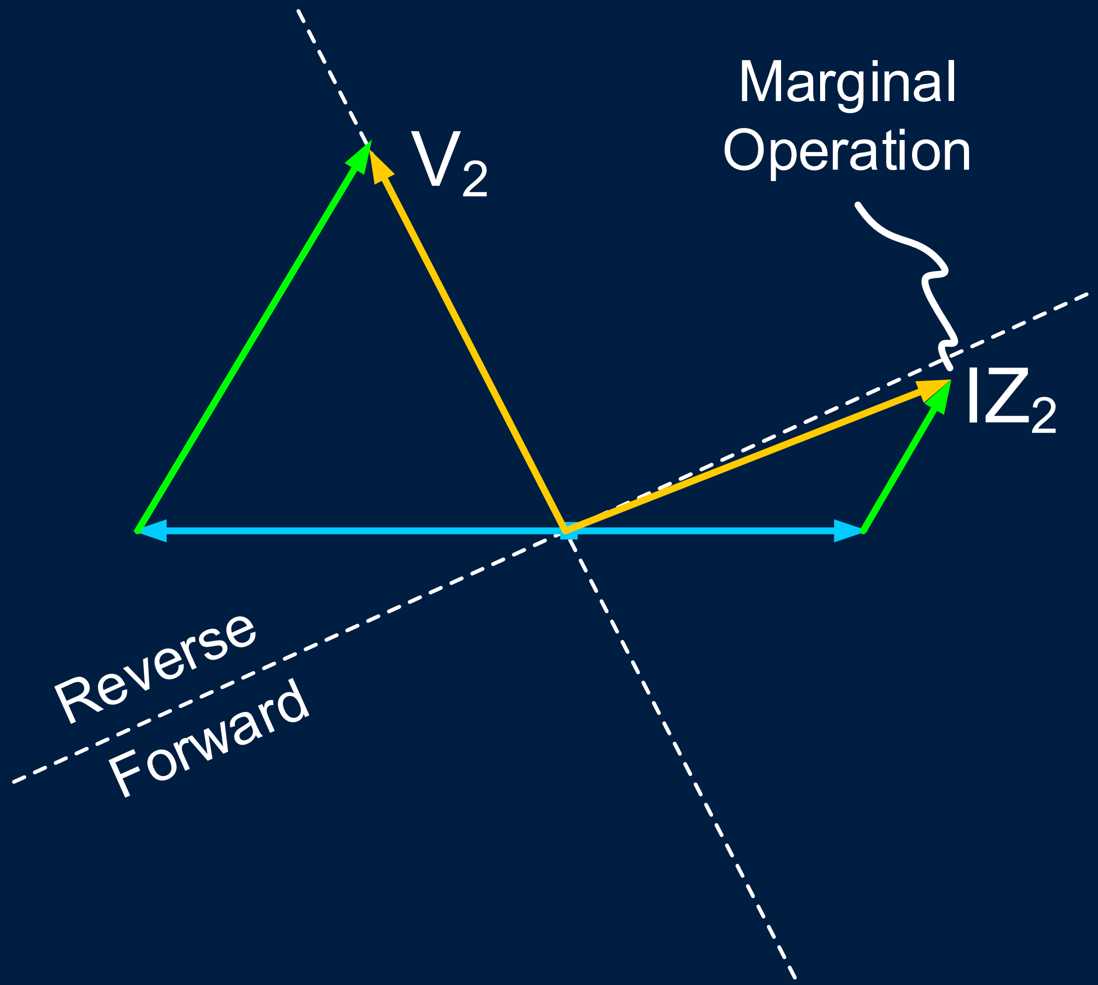


Only Reverse BG Fault Present



Cross-Country Fault Analysis

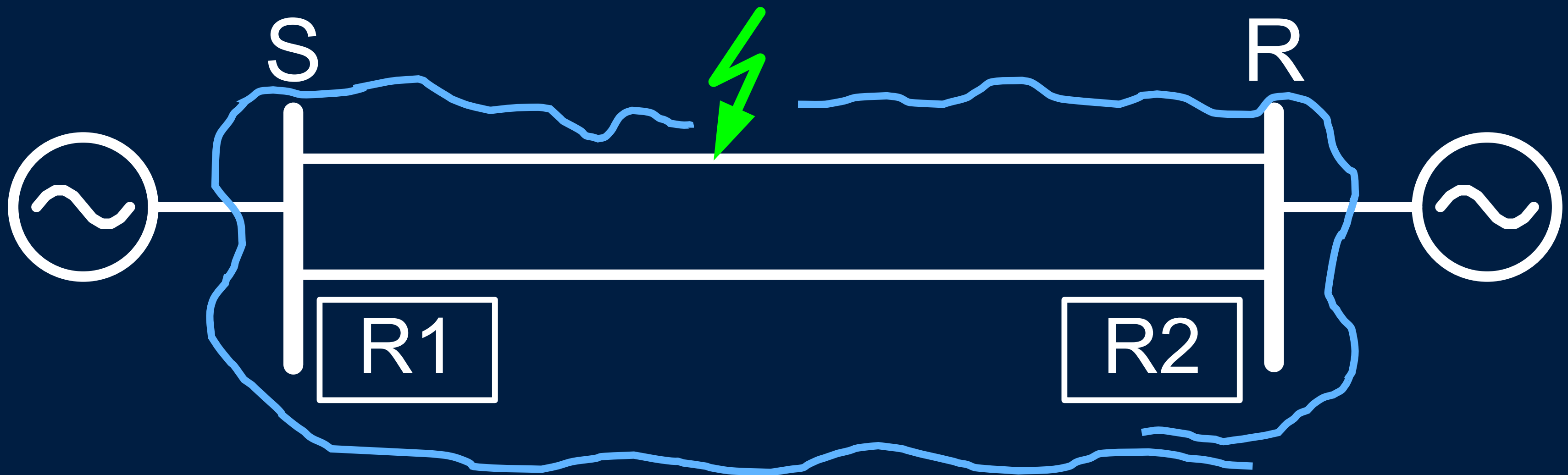
Both Faults Are Present



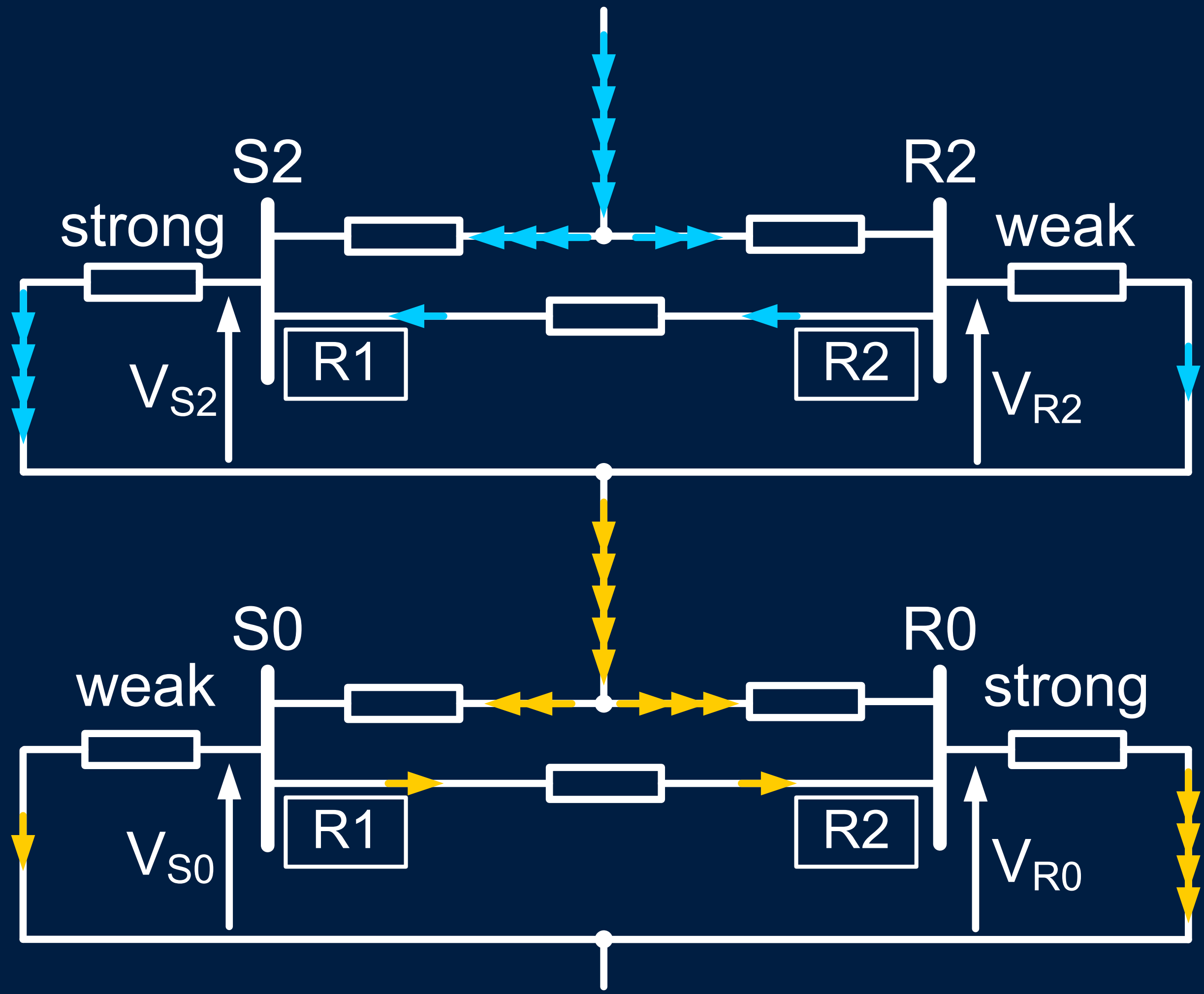
- The polarizing voltage is off by 60°
- Forward or reverse direction asserted based on relative current flow
- 32Q and 32G may respond differently
- Use distance elements rather than 32Q/G

32Q and 32G May Disagree

Forward and Reverse Fault?



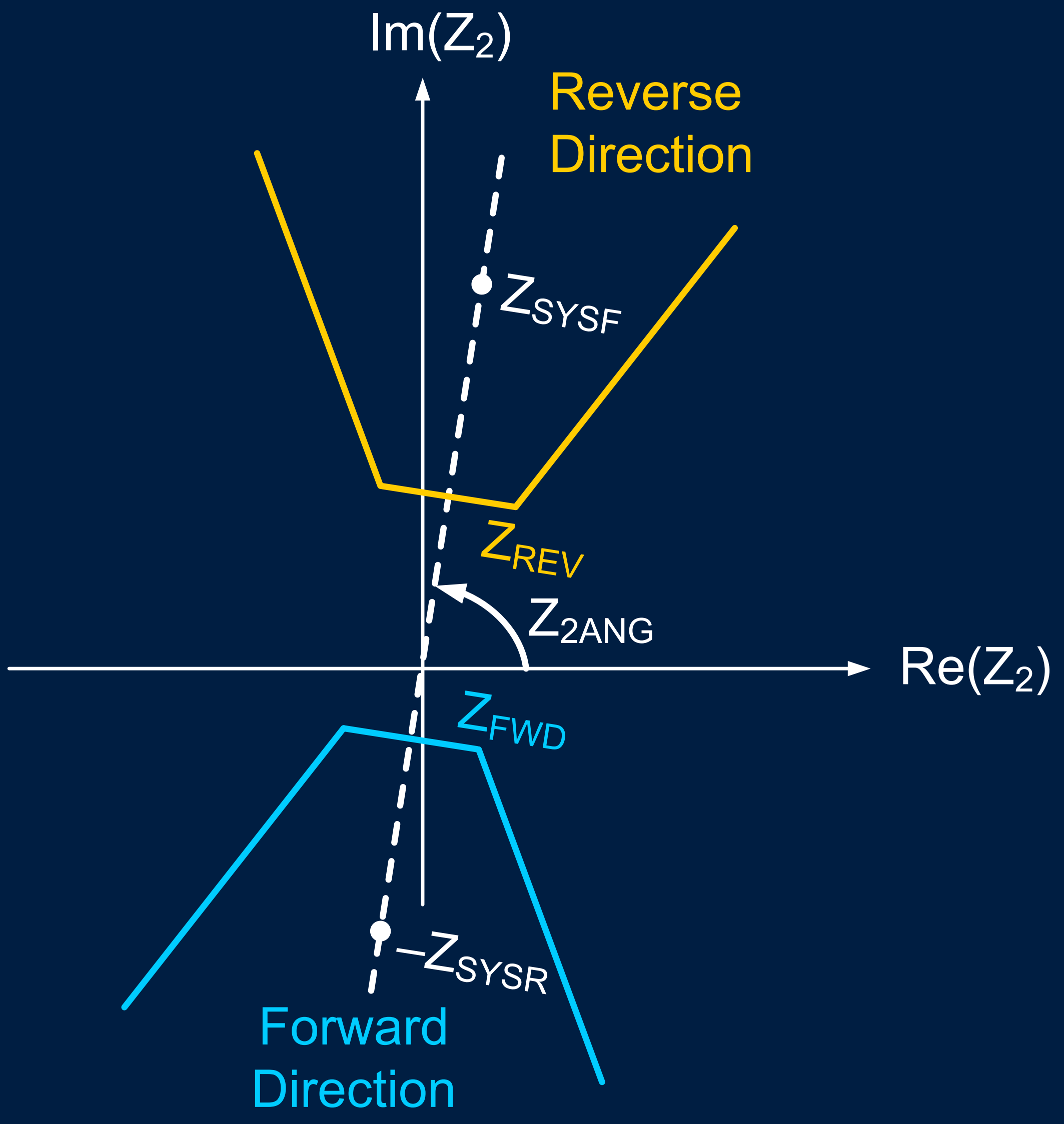
32Q and 32G May Disagree
Forward and Reverse Fault?



- Avoid using multiple sensitive directional elements
- Use separate permissive key signals if needed

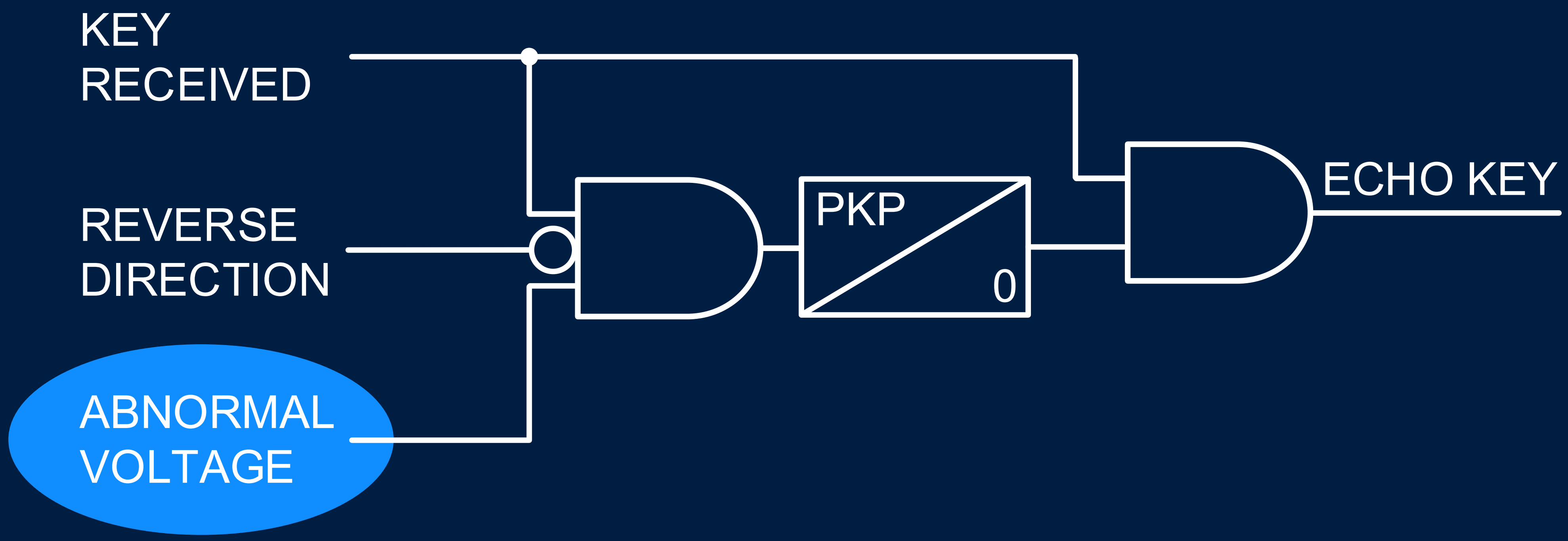
32Q and 32G With Zero Polarizing Voltage

Avoid Unless Necessary

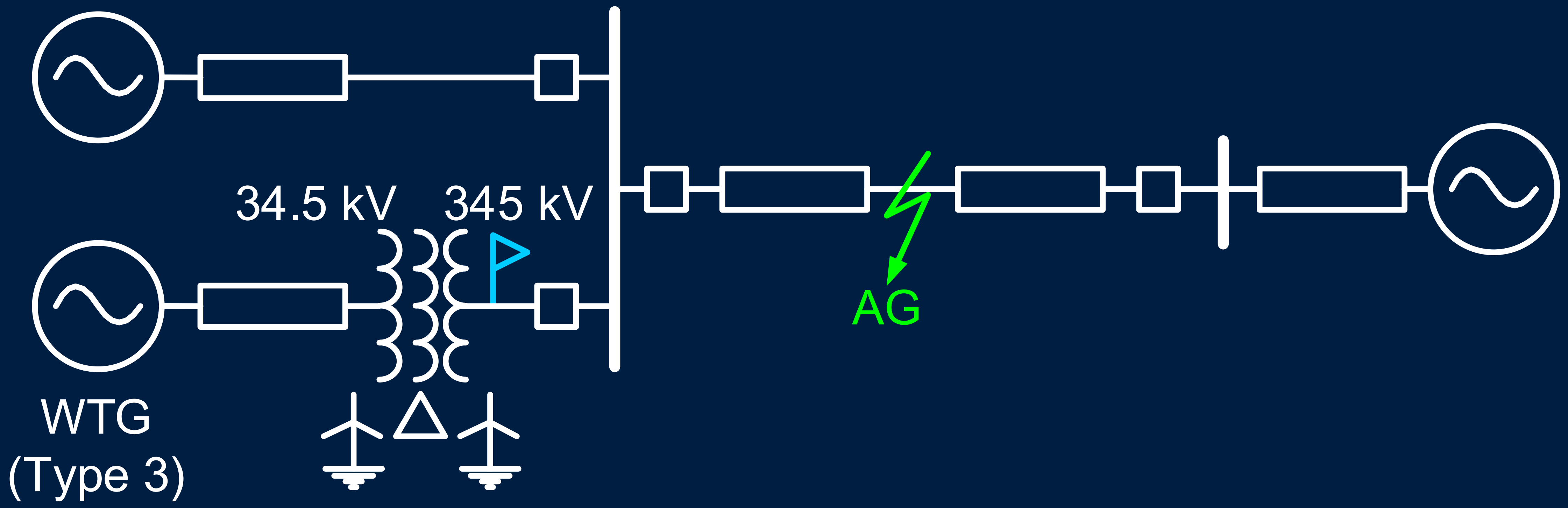


- Many conditions can cause operating current
- If biased forward, 32Q/G would key on many non-fault events
- Use bias only when short-circuit studies show it is a must

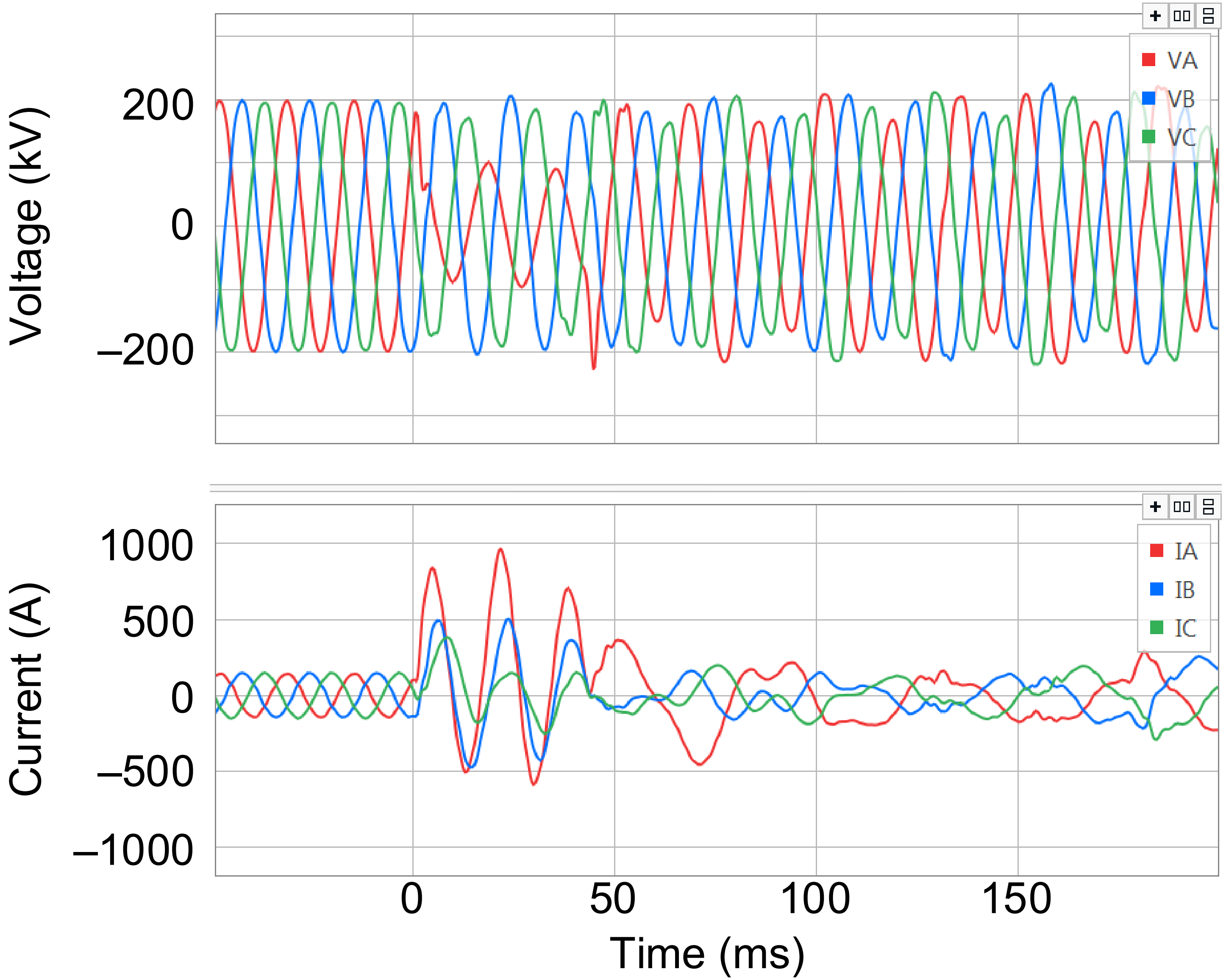
Weak Infeed Logic
Never Key Back if Not Sure There Is a Fault



Nontraditional Sources Drive Sequence Components Differently Than We Expect

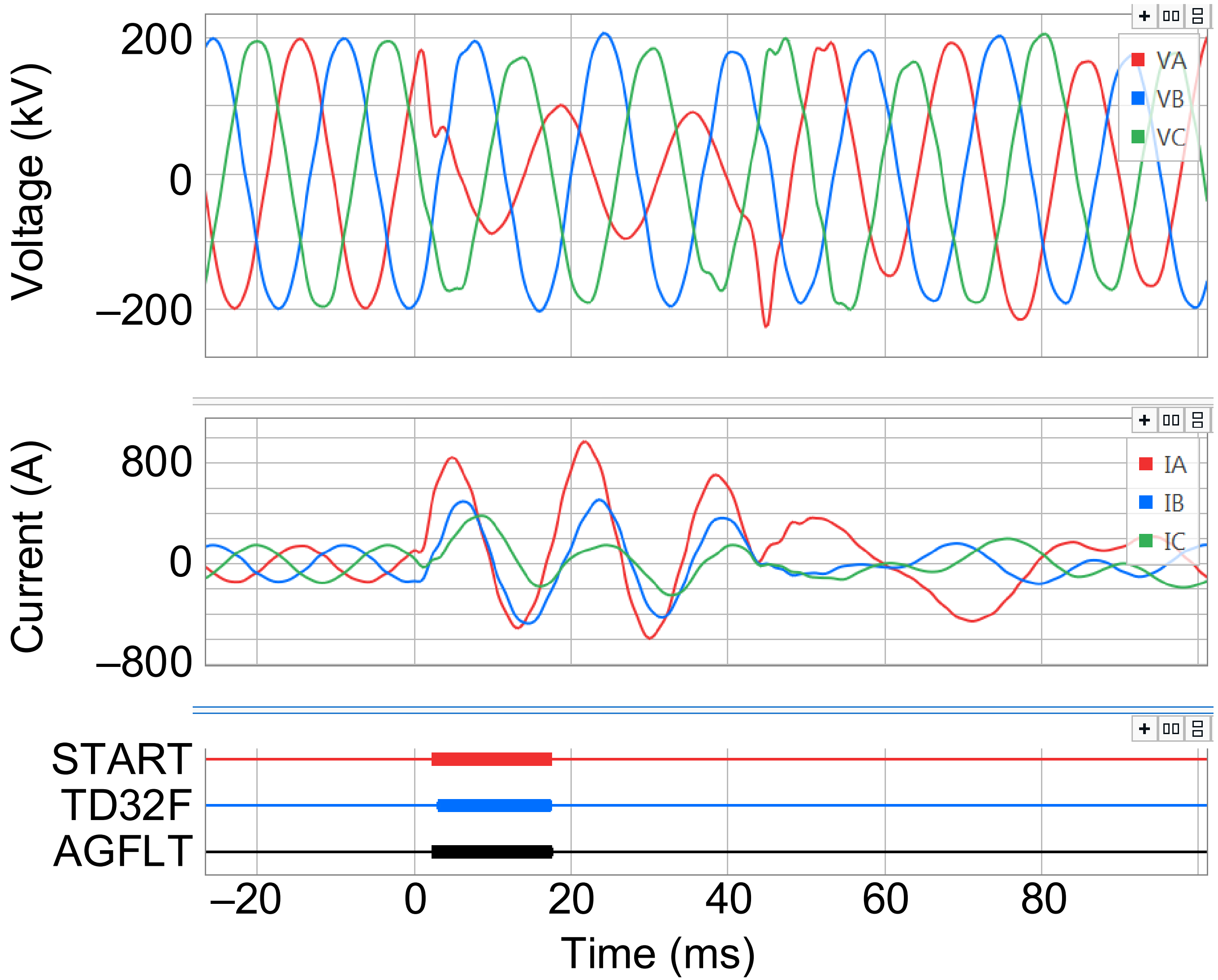


AG Fault Record



- Strong zero-sequence due to transformer ground
- Negative-sequence is low and modulated
- Inverter-based source even more difficult than WTG

Incremental Quantities-Based Relay Performs Very Well



Protection Based on Sequence Components Is Fast and Sensitive, But …

- Responds to many types of events, not only faults
- Works well for a single event
- Requires proper restraining as a part of design
- Calls for careful application
- May face issues with nontraditional sources
- Benefits from phase-based “backup”