Beyond the Nameplate: Transformer Compensation Revisited – New Applications, Greater Simplicity

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Transformer 87R phase angle compensation

- Compensation is based on fundamentals
- Compensation settings are 3 x 3 matrices
- Incorrect settings cause misoperations

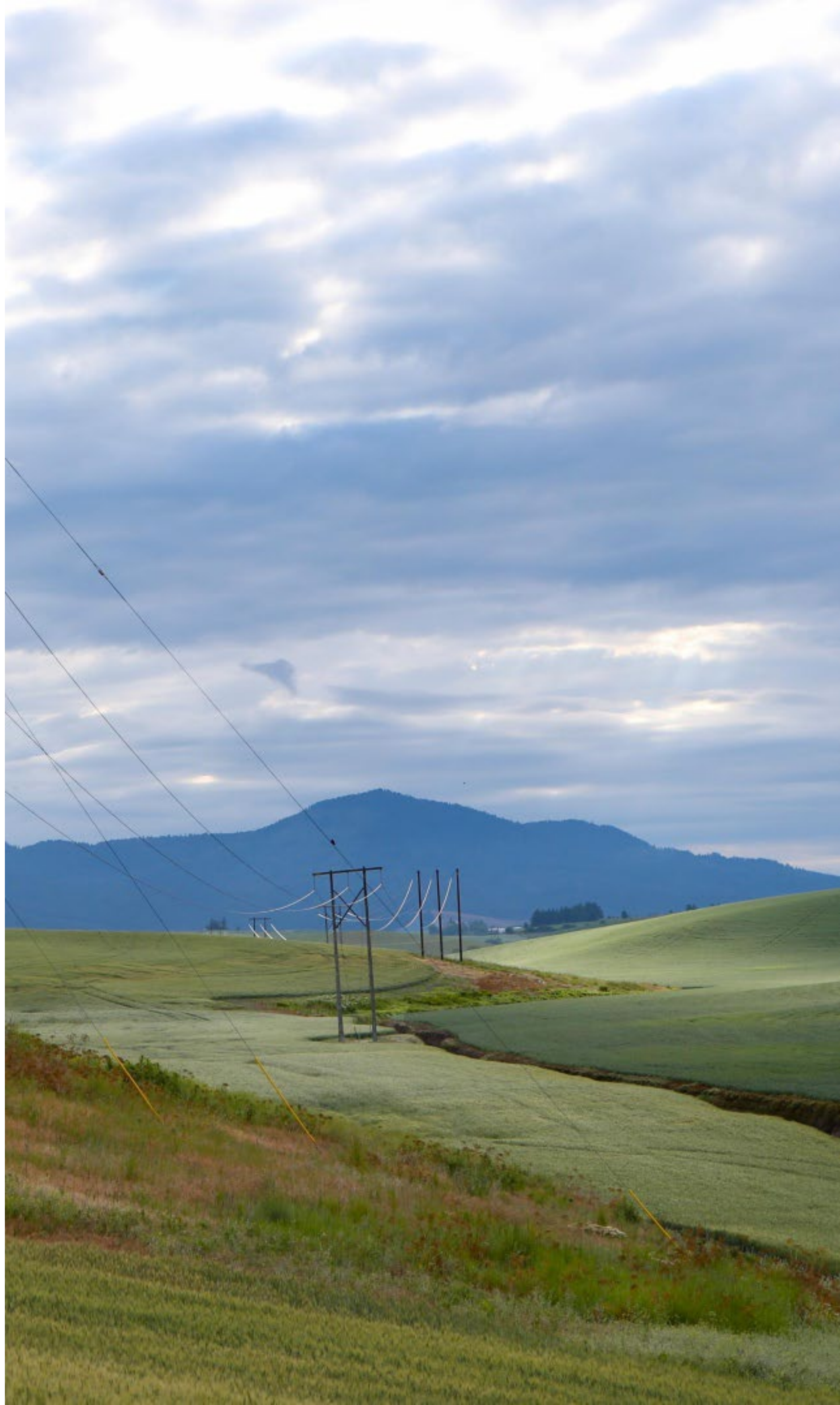
$$\begin{bmatrix} Ia_{compensated} \\ Ib_{compensated} \\ Ic_{compensated} \end{bmatrix} = \begin{bmatrix} \text{Compensation Matrix} \end{bmatrix} \bullet \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

shifts

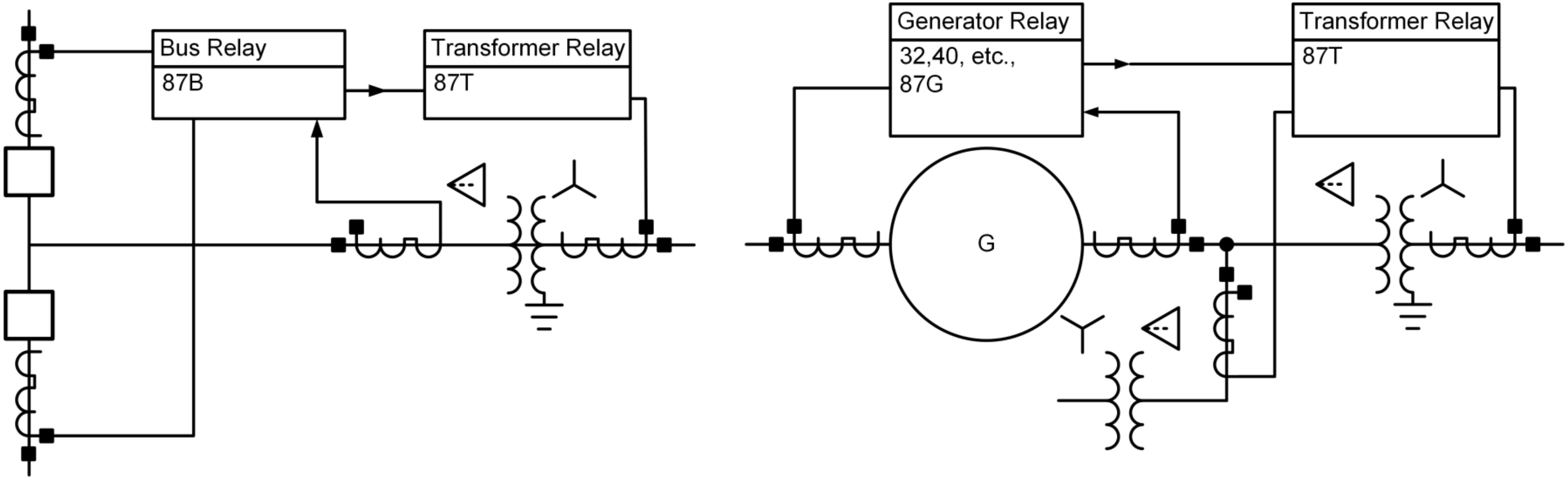
Row	Wye	Delta	Double-Delta
0	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$
1		$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$	
2	$\begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} 1 & -2 & 1 \\ 1 & 1 & -2 \\ -2 & 1 & 1 \end{bmatrix}$
3		$\frac{1}{\sqrt{3}}\begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix}$	
4	$\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} -1 & -1 & 2 \\ 2 & -1 & -1 \\ -1 & 2 & -1 \end{bmatrix}$
5		$\frac{1}{\sqrt{3}}\begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix}$	
6	$\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$
7		$\frac{1}{\sqrt{3}}\begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix}$	
8	$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} -1 & 2 & -1 \\ -1 & -1 & 2 \\ 2 & -1 & -1 \end{bmatrix}$
9		$\frac{1}{\sqrt{3}}\begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix}$	
10	$\begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} 1 & 1 & -2 \\ -2 & 1 & 1 \\ 1 & -2 & 1 \end{bmatrix}$
11		$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$	

Benefits of full set of matrices

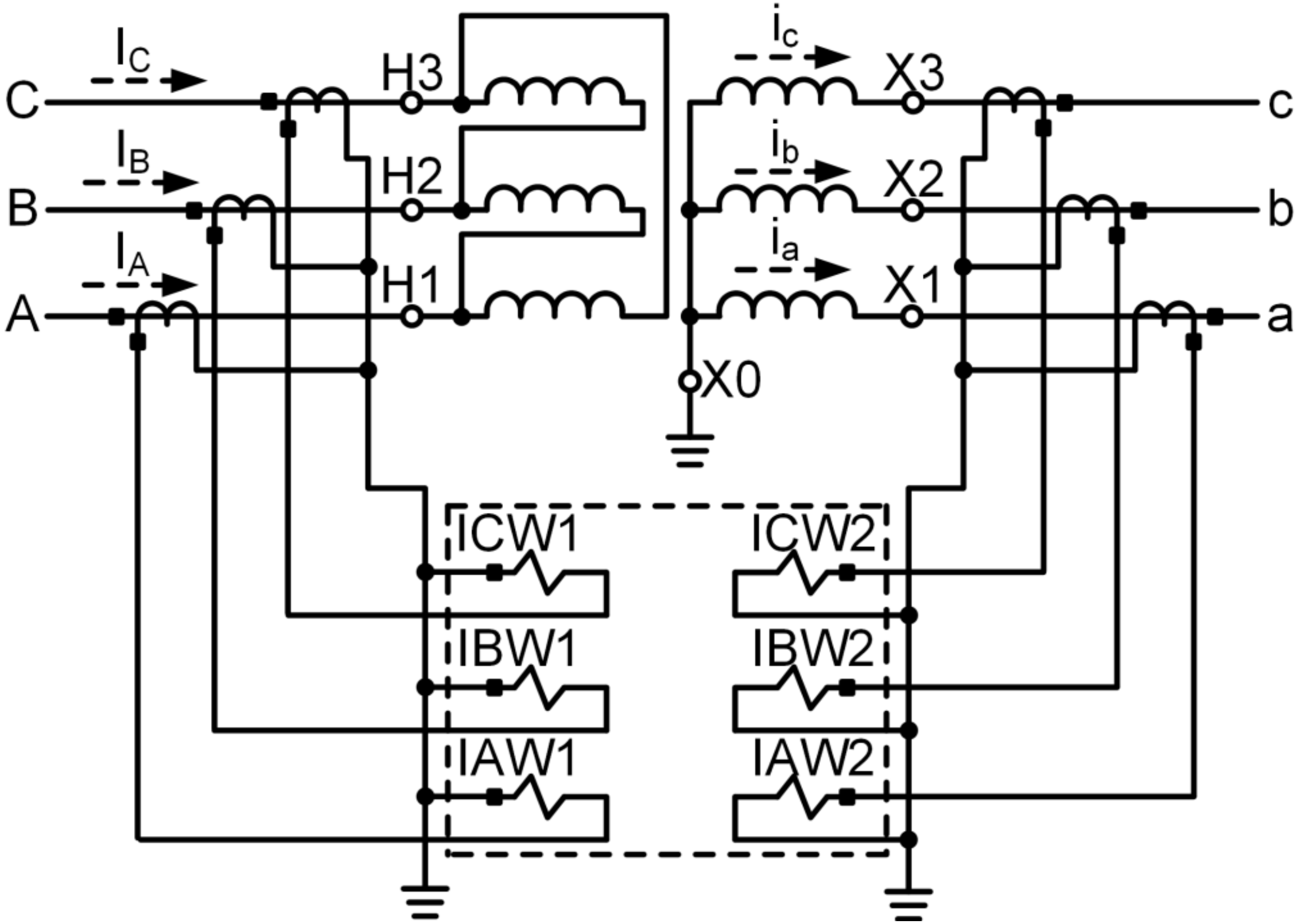
- Any winding can be a reference
- Intuitive compensation settings
- No rolling phases



Inverted CT connections



Example: Dyn1 transformer with inverted CT connections



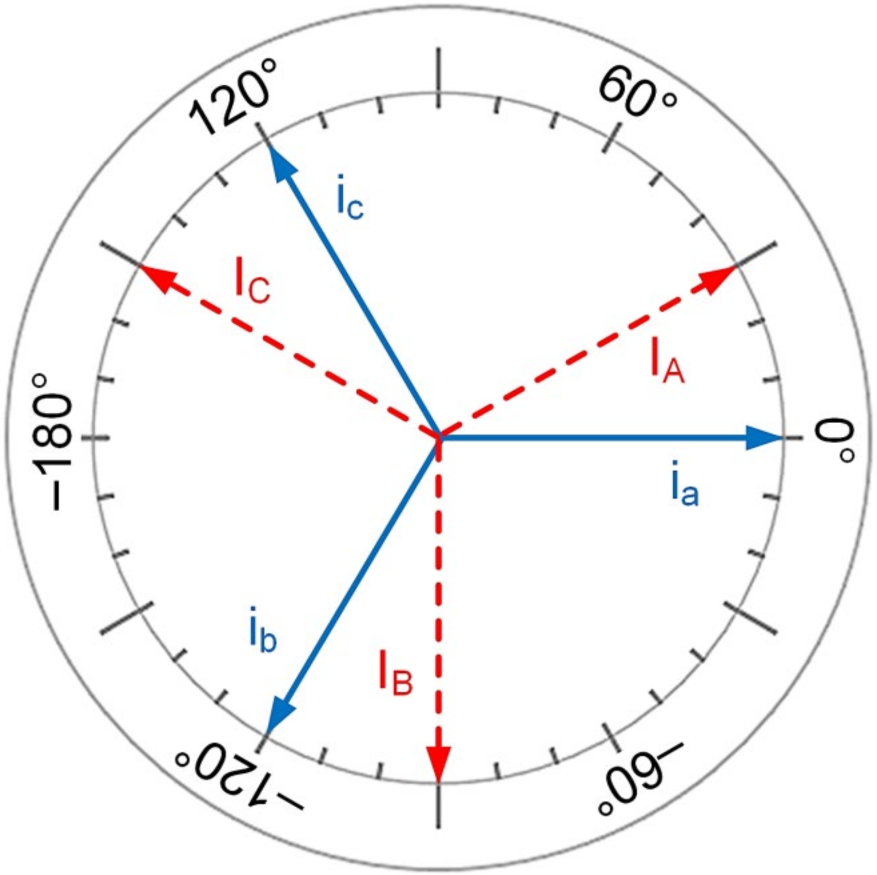
Step 1: Determine reference and nameplate phase shift

Select a reference winding

(Winding 2, wye winding)

Determine number of degrees each winding lags reference, assuming a standard installation

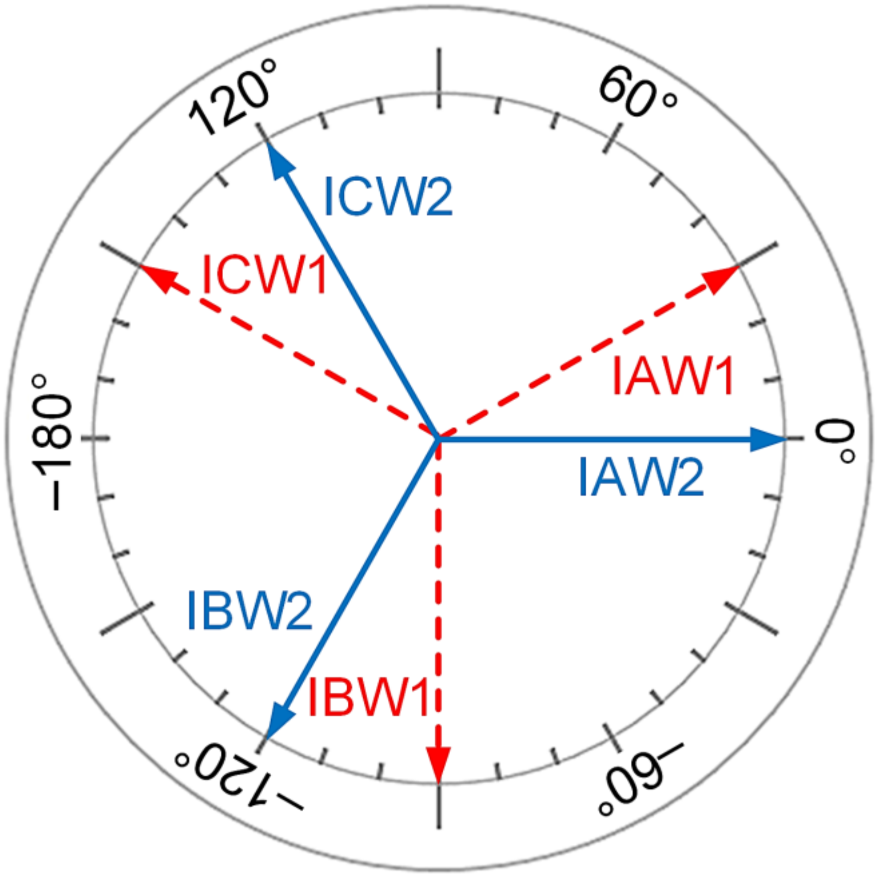
(Winding 1 lags reference by 330°)



Step 2: Determine real phase shift

Determine phase relationship between each winding and reference winding as seen by relay, considering

- System phase sequence
- Phase-to-bushing connections
- CT wiring



Step 3: Select columns

Identify the column of possible matrices that should be used for each winding

- Delta winding ➡ wye matrix
- Wye winding ➡ delta matrix
- Zigzag winding ➡ double-delta matrix

Row	Wye	Delta	Double-Delta
0	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$
1		$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$	
2	$\begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} 1 & -2 & 1 \\ 1 & 1 & -2 \\ -2 & 1 & 1 \end{bmatrix}$
3		$\frac{1}{\sqrt{3}}\begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix}$	
4	$\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} -1 & -1 & 2 \\ 2 & -1 & -1 \\ -1 & 2 & -1 \end{bmatrix}$
5		$\frac{1}{\sqrt{3}}\begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix}$	
6	$\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$
7		$\frac{1}{\sqrt{3}}\begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix}$	
8	$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} -1 & 2 & -1 \\ -1 & -1 & 2 \\ 2 & -1 & -1 \end{bmatrix}$
9		$\frac{1}{\sqrt{3}}\begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix}$	
10	$\begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$		$\frac{1}{3}\begin{bmatrix} 1 & 1 & -2 \\ -2 & 1 & 1 \\ 1 & -2 & 1 \end{bmatrix}$
11		$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$	

Step 4: Select rows

Select compensation for reference winding as lowest-numbered matrix that meets criteria in Step 3

Reference winding gets Delta matrix, row 1

Row	Wye	Delta	Double-Delta
0	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{bmatrix}$
1		$\frac{1}{\sqrt{3}}\begin{bmatrix}1&-1&0\\0&1&-1\\-1&0&1\end{bmatrix}$	
2	$\begin{bmatrix}0&-1&0\\0&0&-1\\-1&0&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}1&-2&1\\1&1&-2\\-2&1&1\end{bmatrix}$
3		$\frac{1}{\sqrt{3}}\begin{bmatrix}0&-1&1\\1&0&-1\\-1&1&0\end{bmatrix}$	
4	$\begin{bmatrix}0&0&1\\1&0&0\\0&1&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-1&-1&2\\2&-1&-1\\-1&2&-1\end{bmatrix}$
5		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1&0&1\\1&-1&0\\0&1&-1\end{bmatrix}$	
6	$\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&-1\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-2&1&1\\1&-2&1\\1&1&-2\end{bmatrix}$
7		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1&1&0\\0&-1&1\\1&0&-1\end{bmatrix}$	
8	$\begin{bmatrix}0&1&0\\0&0&1\\1&0&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-1&2&-1\\-1&-1&2\\2&-1&-1\end{bmatrix}$
9		$\frac{1}{\sqrt{3}}\begin{bmatrix}0&1&-1\\-1&0&1\\1&-1&0\end{bmatrix}$	
10	$\begin{bmatrix}0&0&-1\\-1&0&0\\0&-1&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}1&1&-2\\-2&1&1\\1&-2&1\end{bmatrix}$
11		$\frac{1}{\sqrt{3}}\begin{bmatrix}1&0&-1\\-1&1&0\\0&-1&1\end{bmatrix}$	

Step 4 (continued…)

Determine number of degrees each winding must be shifted to plot 180° out of phase with reference after compensation

Winding 1 must be shifted 180° ccw

Divide number by 30° to select row

180° / 30° = 6

Row	Wye	Delta	Double-Delta
0	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{bmatrix}$
1		$\frac{1}{\sqrt{3}}\begin{bmatrix}1&-1&0\\0&1&-1\\-1&0&1\end{bmatrix}$	
2	$\begin{bmatrix}0&-1&0\\0&0&-1\\-1&0&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}1&-2&1\\1&1&-2\\-2&1&1\end{bmatrix}$
3		$\frac{1}{\sqrt{3}}\begin{bmatrix}0&-1&1\\1&0&-1\\-1&1&0\end{bmatrix}$	
4	$\begin{bmatrix}0&0&1\\1&0&0\\0&1&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-1&-1&2\\2&-1&-1\\-1&2&-1\end{bmatrix}$
5		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1&0&1\\1&-1&0\\0&1&-1\end{bmatrix}$	
6	$\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&-1\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-2&1&1\\1&-2&1\\1&1&-2\end{bmatrix}$
7		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1&1&0\\0&-1&1\\1&0&-1\end{bmatrix}$	
8	$\begin{bmatrix}0&1&0\\0&0&1\\1&0&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-1&2&-1\\-1&-1&2\\2&-1&-1\end{bmatrix}$
9		$\frac{1}{\sqrt{3}}\begin{bmatrix}0&1&-1\\-1&0&1\\1&-1&0\end{bmatrix}$	
10	$\begin{bmatrix}0&0&-1\\-1&0&0\\0&-1&0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}1&1&-2\\-2&1&1\\1&-2&1\end{bmatrix}$
11		$\frac{1}{\sqrt{3}}\begin{bmatrix}1&0&-1\\-1&1&0\\0&-1&1\end{bmatrix}$	

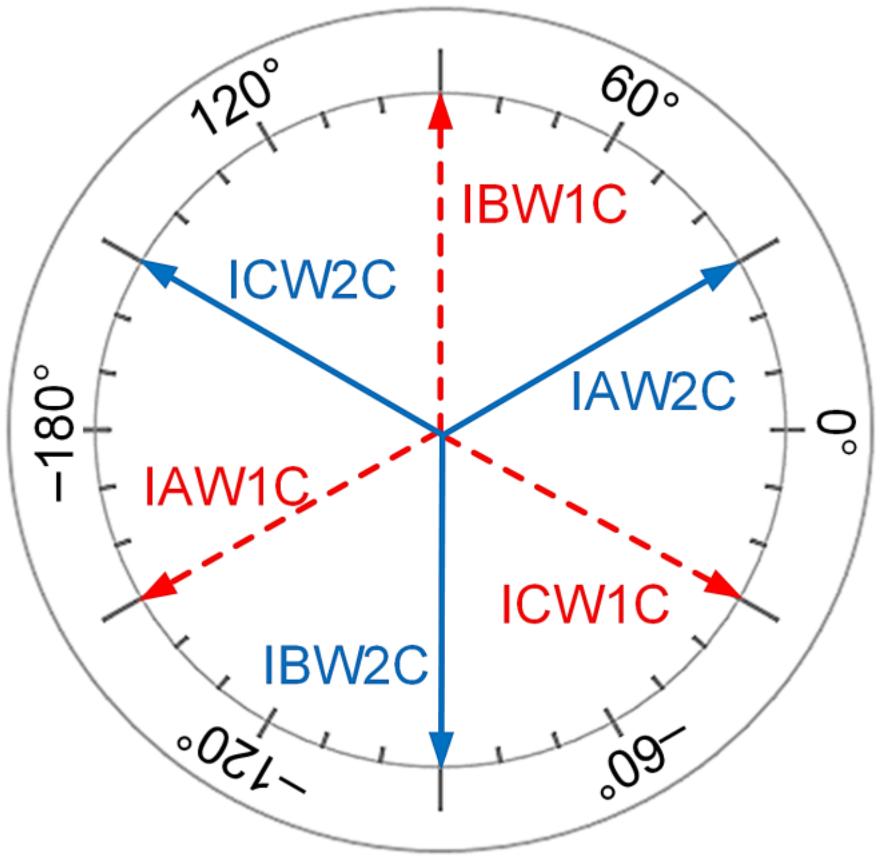
Final solution

Solution for Dyn1 installation with incorrect wiring

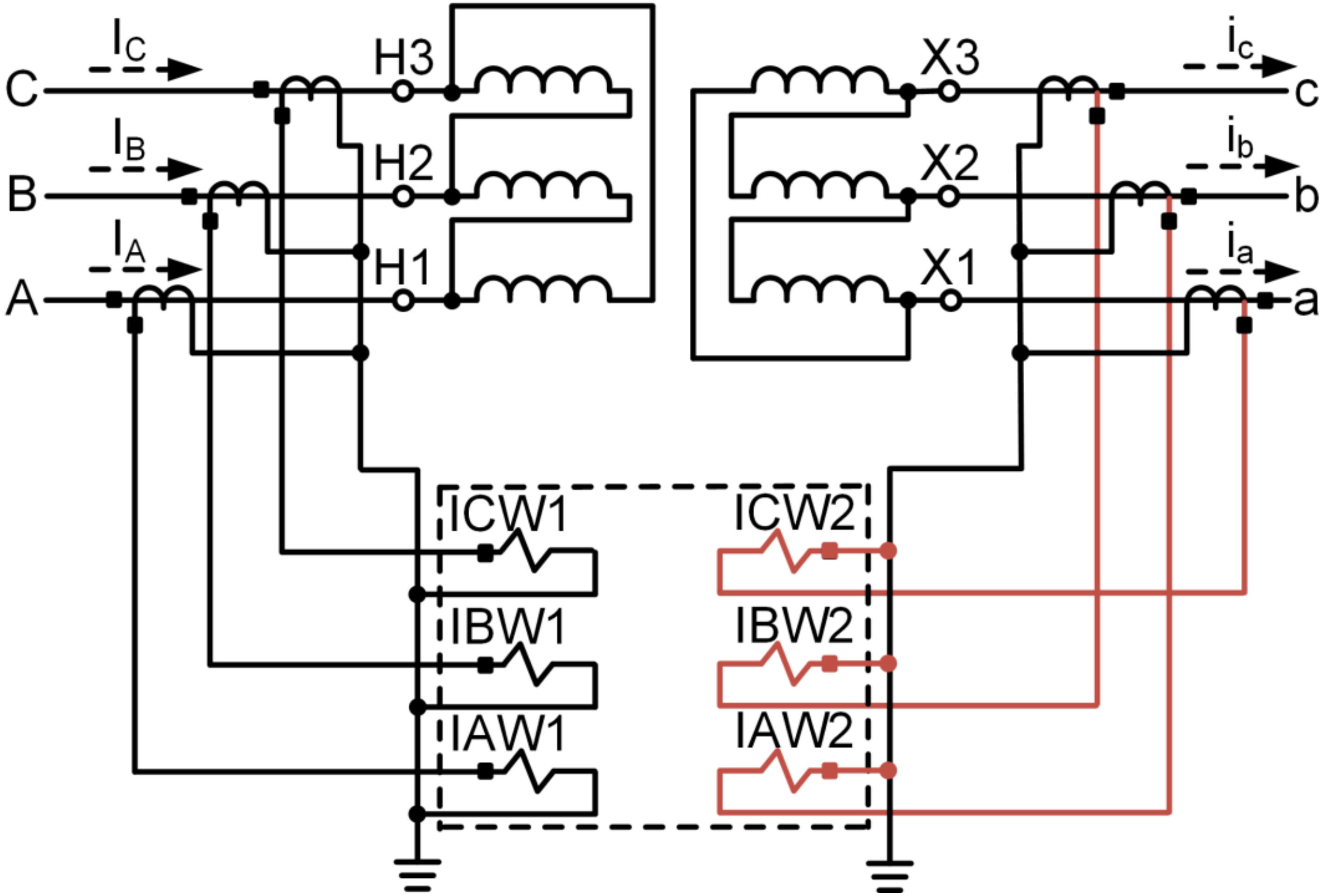
- Delta winding = Wye matrix, row 6
- Wye winding = Delta matrix, row 1

Solution for Dyn1 installation with correct wiring

- Delta winding = Wye matrix, row 0
- Wye winding = Delta matrix, row 1

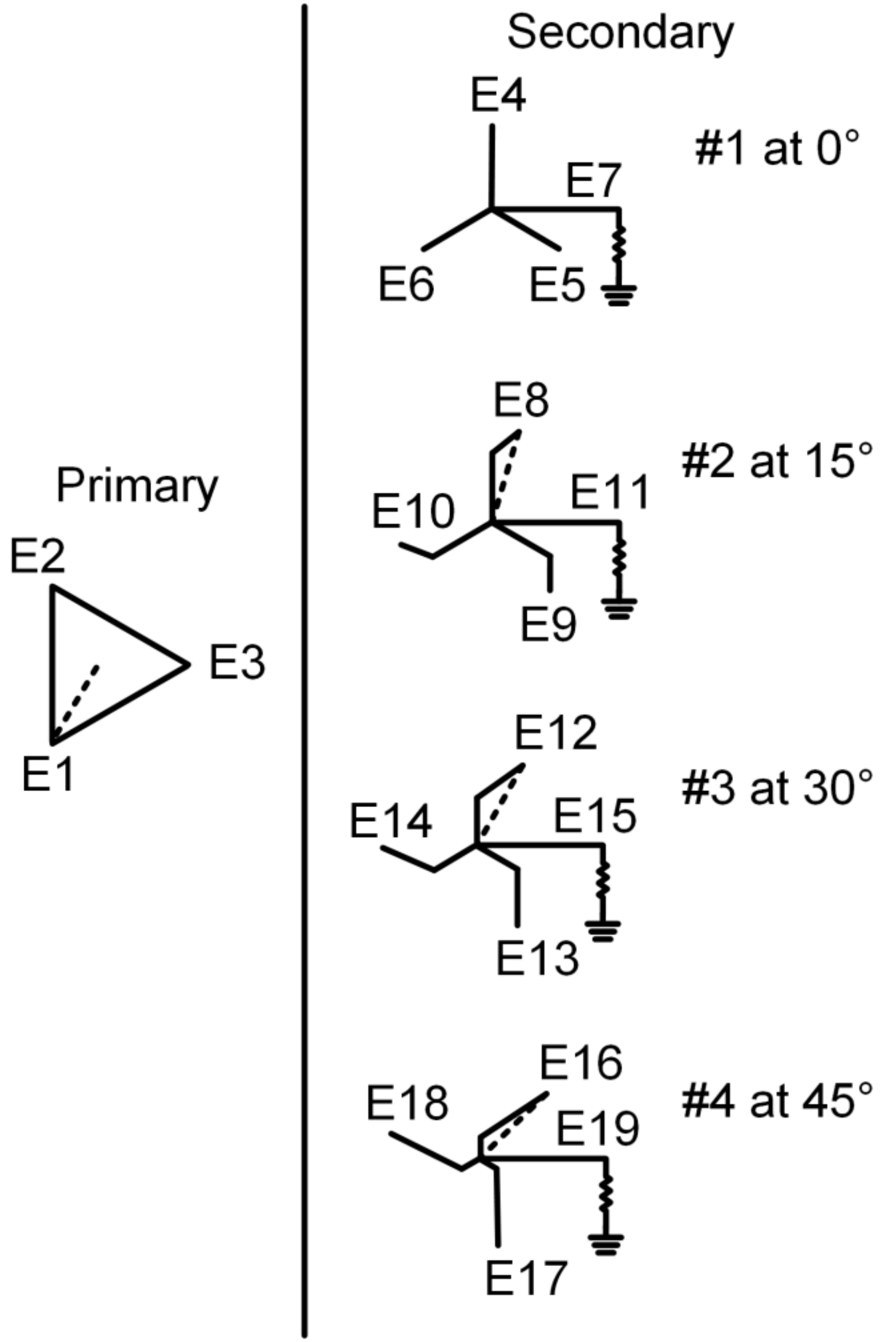


Example: Dd2 transformer



- Limited matrices requires using delta winding as reference (which delta winding?)
  - Compensate externally by swapping phases at relay terminals
  - Compensate with unintuitive settings
    - Winding 1 = Delta matrix, row 1
    - Winding 2 = Delta matrix, row 3
- All matrices give intuitive settings
  - Winding 1 = Wye matrix, row 0
  - Winding 2 = Wye matrix, row 2

Nonstandard phase shifts



Zero Sequence Removal	Matrix
ZSR = Y	$\frac{2}{3}\begin{bmatrix} \cos(\phi) & \cos(\phi+120^\circ) & \cos(\phi-120^\circ) \\ \cos(\phi-120^\circ) & \cos(\phi) & \cos(\phi+120^\circ) \\ \cos(\phi+120^\circ) & \cos(\phi-120^\circ) & \cos(\phi) \end{bmatrix}$
ZSR = N	$\frac{2}{3}\begin{bmatrix} 0.5+\cos(\phi) & 0.5+\cos(\phi+120^\circ) & 0.5+\cos(\phi-120^\circ) \\ 0.5+\cos(\phi-120^\circ) & 0.5+\cos(\phi) & 0.5+\cos(\phi+120^\circ) \\ 0.5+\cos(\phi+120^\circ) & 0.5+\cos(\phi-120^\circ) & 0.5+\cos(\phi) \end{bmatrix}$

Conclusions

- Continue to use original “Beyond the Nameplate” rules when limited set of matrices are available
- Use procedure in this paper when all matrices are available
- Use generalized matrices for nonstandard phase shifts

Questions?