Calculating the short circuit current and input impedance of each node in the power system (by matrix methods)
The conventional form of the load flow equations:

$$I_{bus} = Y_{bus} \cdot V_{bus}$$

$$V_{bus} = Z_{bus} \cdot I_{bus}$$

$$Z_{bus} = Y_{bus}^{-1}$$
System Equations Summary (2)

- $V_{bus}$ is the vector of complex voltage phasors on each bus.
- The elements of $V_{bus}$ are complex numbers.

$$V_{bus} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}$$
System Equations Summary (2)

- $\mathbf{I}_{\text{bus}}$ is the vector of injected currents into each bus.
- The elements of $\mathbf{I}_{\text{bus}}$ are also complex numbers.
- In normal operation, each injection can be:
  - from a generator (+)
  - or into a load (-)
- In abnormal circumstances and operation an injection can feed into a short circuit

\[
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
\vdots \\
I_n
\end{bmatrix}
\]
Let us review a previous equation describing the system.

There is 1 “injection” of current at bus #3.

This is now the fault current but it could as well be a current from a generator.

The resulting bus voltage changes are on the left hand side.

Multiply the 3rd row by the column vector and we get.

The \( z'_{33} \) element in the modified \( Z_{bus} \) matrix is the input impedance at node #3.

\[
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
\vdots \\
V_n
\end{bmatrix} =
\begin{bmatrix}
z'_{11} & z'_{12} & \cdots & z'_{1n} \\
z'_{21} & z'_{22} & \cdots & z'_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
z'_{n1} & z'_{n2} & \cdots & z'_{nn}
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
I_3 \\
\vdots \\
0
\end{bmatrix}
\]

\[
V_3 = z'_{31} \cdot 0 + z'_{32} \cdot 0 + z'_{33} \cdot I_3 + z'_{34} \cdot 0 + \ldots + z'_{3n} \cdot 0
\]

\[
V_3 = z'_{33} \cdot I_3
\]

\[
I_3 = \frac{V_3}{z'_{33}} = \frac{V_3}{Z_{in,3}}
\]
We get 2 equivalent circuits:

By the previous matrix calculations the power system has been reduced to a single **Thevenin equivalent circuit**

\[
\Delta V_1 \quad \Delta V_2 \quad I_{3,\text{fault}} \quad V_{3,0} \quad Z_f
\]

\[
z_{33}' = z_{in,3}
\]

The power system
Calculation of fault currents

- The general equation for calculating the fault current from the previous simple circuit is therefore:

- **The most important element is the diagonal element of the modified impedance matrix,** $z'_{33}$

- If we have a solid fault $z_f = 0$ and the fault current takes its maximum or:
  - $V_{3,0}$ is the pre-fault voltage at node 3
  - $I_{3,fault}$ is the short circuit current
  - $z'_{33}$ is the input impedance at node 3

$$I_{3,fault} = \frac{V_{3,0}}{z_f + z'_{33}}$$

$$I_{3,fault} = \frac{V_{3,0}}{z'_{33}}$$
A Short Circuit Calculation Algorithm (A review)

1. Define the power system and its operational conditions
2. Calculate the pre-fault power flow and calculate pre-fault voltages and currents
3. Calculate the internal impedance (input impedance) and pre-fault voltage (Thevenin equivalent circuit)
4. Calculate the fault currents (i.e. system wide changes of currents)
5. Calculate the post fault currents as the sum of the pre-fault currents and the fault currents (by the superposition principle)
Fault Current Calculations (A review)

- Pre-fault currents $I_0$ (load currents) are usually in phase or near in phase with the voltage.
- The fault currents $I_f$ are primarily inductive, i.e. out of phase with the voltage.
- Short circuit currents $I_f$ >> load currents
- Power system components are reactive
- Load components are resistive
- Pre-fault load currents can often be ignored

$V$ $I_0$ $I_f$ $I_0 + I_f$
Building the matrix “from scratch” in many steps adding one element at a time
Building the $Z_{bus}$ matrix directly

- It is often difficult to invert the $Y_{bus}$ matrix by traditional matrix inversion methods.
- The $Y_{bus}$ matrix is **symmetric** and usually large and sparse.
- The $Z_{bus}$ matrix is **symmetric** and **full** (and usually large).
- We often need to change the configuration of the underlying power system, (for instance in contingencies where a single link is added/deleted).
  - We need to remove a line or add a transmission line or a link.
- A **direct step-by-step matrix building method** is advantageous.
The $Z_{bus}$ matrix can be built step by step by a direct method rather than calculating $Y_{bus}^{-1}$.

Consider a general $n$-bus power system.

We add one link at a time.

In each step, we transform the matrix as follows:

$Z_{bus, old} \rightarrow Z_{bus, new}$

The earth is a special node = “reference node”
**Z_{bus} building algorithm**

- **As an example** take a 3-bus system with 5 impedances (links).
- We build the full matrix in 5 steps and add 1 impedance at a time.
- The $Z_{bus}$ matrix is defined as follows:

  \[
  V_{bus} = Z_{bus} \cdot I_{bus}
  \]

  \[
  Z_{bus} = Y_{bus}^{-1}
  \]

  \[
  \begin{align*}
  v_1 &= z_{11}i_1 + z_{12}i_2 + z_{13}i_3 \\
  v_2 &= z_{21}i_1 + z_{22}i_2 + z_{23}i_3 \\
  v_3 &= z_{31}i_1 + z_{32}i_2 + z_{33}i_3
  \end{align*}
  \]
5 steps in $Z_{bus}$ building algorithm

- $Z_{bus}$ is going to be a 3x3 matrix built in 5 steps:

1st step

2nd step

3rd step

4th step

5th step
4 different types of steps

1. Add a new node and from it a new branch to ground
2. Add a new node and from it a new branch to an existing node
3. Add a new branch between 2 existing nodes
4. Add a new branch from an existing node to ground
Numerical network example in building $Z_{\text{bus}}$

- Consider also the following numerical example
- Assume we have 5 impedances and 3 buses
- Again, we build the matrix in 5 steps
- The branches in the numerical example have impedance values:

\[
z_1 = j0.15 \quad z_2 = j0.075 \quad z_3 = j0.1 \quad z_4 = j0.1 \quad z_5 = j0.1
\]
The 1st step in the $Z_{bus}$ building algorithm

- We add branch and inject a current at any node \#1 and get a voltage there 
  \[ v_1 = z_1 i_1 \]

  \[ v_1 = z_{11} i_1 + z_{12} i_2 + z_{13} i_3 \]

  \[ v_2 = z_{21} i_1 + z_{22} i_2 + z_{23} i_3 \]

  \[ v_3 = z_{31} i_1 + z_{32} i_2 + z_{33} i_3 \]

- By comparing the above equations we see that the $Z_{bus}$ matrix after this step is a 1x1 (single element):

  \[ Z_{bus} = \begin{bmatrix} z_1 \end{bmatrix} \]
The **1st step** in the $Z_{bus}$ building algorithm

In our numerical example:

$$z_1 = j0.15, \quad z_2 = j0.075, \quad z_3 = j0.1,$$

$$z_4 = j0.1 \text{ and } z_5 = j0.1$$

Therefore $Z_{bus} = [z_1] = [j0.15]$
The 2nd step in the $Z_{bus}$ building algorithm

- We now add a branch to the reference node from a node (#2) not previously connected

\[
v_1 = z_1 i_1 + 0 \cdot i_2
\]
\[
v_2 = 0 \cdot i_1 + z_2 i_2
\]

- The $Z_{bus}$ will now be a 2x2:

\[
V_{bus} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} z_1 & 0 \\ 0 & z_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}
\]
\[
Z_{bus(old)} = \begin{bmatrix} z_1 \end{bmatrix}
\]
\[
Z_{bus(new)} = \begin{bmatrix} Z_{bus(old)} & 0 \\ 0 & z_2 \end{bmatrix}
\]
The 2nd step in the $Z_{bus}$ building algorithm (2)

- Assume $Z_{bus,old}$ is a matrix of dimension $(k \times k)$
- We want to add a node ($\# k+1$) that has not previously been added to our set of nodes.
- From this node we add the new impedance, $z_{new}$, to the reference node.
- We transform $Z_{bus,old}$ to $Z_{bus,new}$ by adding a row and a column to the $Z_{bus,old}$ ($\# k+1$).
- Add zeros to all elements of the new row and column except the new diagonal element which is the new impedance, $z_{new}$.
- The dimensions of the matrix are increased by 1 and are now $(k+1)$ times $(k+1)$. 

$$Z_{bus,new} = \begin{bmatrix} \vdots & \vdots & \vdots \\ 0 & \cdots & 0 \\ \end{bmatrix} + \begin{bmatrix} \vdots \\ 0 \\ \end{bmatrix}$$

$$= \begin{bmatrix} \vdots & \vdots & \vdots \\ 0 & \cdots & 0 \\ \end{bmatrix} + \begin{bmatrix} \vdots \\ 0 \\ \end{bmatrix}$$

$$= \begin{bmatrix} \vdots & \vdots & \vdots \\ 0 & \cdots & 0 \\ \end{bmatrix} + \begin{bmatrix} \vdots \\ 0 \\ \end{bmatrix}$$
The 2nd step in the $Z_{bus}$ building algorithm

In our numerical example we get in step #2:

\[
V_{bus} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} z_1 & 0 \\ 0 & z_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}
\]

\[
Z_{bus(old)} = \begin{bmatrix} z_1 \end{bmatrix} = \begin{bmatrix} j0.15 \end{bmatrix}
\]

\[
Z_{bus(new)} = \begin{bmatrix} Z_{bus(old)} & 0 \\ 0 & z_2 \end{bmatrix} = \begin{bmatrix} j0.15 & 0 \\ 0 & j0.075 \end{bmatrix}
\]

\[
V_1, V_2, V_3, i_1, i_2, i_3, Z_1, Z_2
\]
The 3rd step in the $Z_{bus}$ building algorithm

- We now add a branch to a previously connected node (#2) from a new node (#3), not previously connected.

- We have the following equations:

\[
\begin{bmatrix}
v_1 \\
v_2 \\
v_3
\end{bmatrix} =
\begin{bmatrix}
z_1 & 0 \\
0 & z_2 \\
0 & z_2
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 + i_3 \\
i_2 + i_3
\end{bmatrix}
\]

\[
v_3 = v_2 + z_4 i_3
\]

\[
\begin{bmatrix}
v_1 \\
v_2 \\
v_3
\end{bmatrix} =
\begin{bmatrix}
z_1 & 0 & 0 \\
0 & z_2 & z_2 \\
0 & z_2 & z_2 + z_4
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
i_3
\end{bmatrix}
\]

\[
Z_{bus,new} = \begin{bmatrix}
Z_{bus,old} & z_{12} \\
z_{12} & z_{22}
\end{bmatrix}
\begin{bmatrix}
z_2 + z_4
\end{bmatrix}
\]
The 3rd step in the $Z_{bus}$ building algorithm (2)

- Assume $Z_{bus,old}$ is a matrix of dimension ($k \times k$)
- We want to add a node (# $k+1$) that has not previously been added to our set of nodes.
- From this node we add the new impedance, $z_{new}$ to a previously connected node (# $j$)
- We transform $Z_{bus,old}$ to $Z_{bus,new}$ by adding a row (number $k+1$) and a column (number $k+1$) to the $Z_{bus,old}$
- Duplicate row/column # $j$ in $Z_{bus,old}$ as the new row/column. The new diagonal element is found by adding the new impedance $z_{new}$ to the diagonal element $z_{jj}$ of $Z_{bus,old}$
- The dimensions of the matrix are increased by 1

$$Z_{bus,new} = \begin{bmatrix}
Z_{j1} & Z_{j2} & \cdots & Z_{jk} \\
Z_{1j} & Z_{1j} & \cdots & Z_{1j} \\
Z_{2j} & \vdots & \ddots & \vdots \\
Z_{kj} & \vdots & \ddots & Z_{jj} + z_{new}
\end{bmatrix}$$
The 3rd step in the $Z_{bus}$ building algorithm

In our numerical example:

$z_1 = j0.15, z_2 = j0.075, z_3 = j0.1, z_4 = j0.1$ and $z_5 = j0.1$

Therefore:

$$\begin{bmatrix}
v_1 \\
v_2 \\
v_3 \\
\end{bmatrix} =
\begin{bmatrix}
z_1 & 0 & 0 \\
0 & z_2 & z_2 \\
0 & z_2 & z_2 + z_4 \\
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
i_3 \\
\end{bmatrix}$$

$$= \begin{bmatrix}
j0.15 & 0 & 0 \\
0 & j0.075 & j0.075 \\
0 & j0.075 & j0.175 \\
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
i_3 \\
\end{bmatrix}$$
The 3rd step in the $Z_{bus}$ building algorithm

Therefore, in our numerical example, after the 3rd step:

$$Z_{bus} = \begin{bmatrix} 
  j0.15 & 0 & 0 \\
  0 & j0.075 & j0.075 \\
  0 & j0.075 & j0.175 
\end{bmatrix}$$
The 4th step in the $Z_{bus}$ building algorithm (1)

- We now add a branch between 2 previously connected nodes (#1) and (#2)
- This new impedance, $z_3 = z_{new}$ in general causes a circular current, $i_L$ to flow.
- The circular current is equivalent to an extra injected current of $+i_L$ at node #1 and of $-i_L$ at node #2
- For the 3 x 3 matrix in the figure, this is equivalent to the following adjustments of the voltage/current equations

$$
\begin{bmatrix}
    v_1 \\
    v_2 \\
    v_3
\end{bmatrix}
= 
\begin{bmatrix}
    z_{11} & z_{12} & z_{13} \\
    z_{21} & z_{22} & z_{23} \\
    z_{31} & z_{32} & z_{33}
\end{bmatrix}
\begin{bmatrix}
    i_1 + i_L \\
    i_2 - i_L \\
    i_3
\end{bmatrix}
$$
The 4th step in the \( Z_{\text{bus}} \) building algorithm

(2)

- In general, assume \( Z_{\text{bus,old}} \) is a matrix of dimension \((k \times k)\).
- Assume that a new element, \( z_{\text{new}} \) is added between node \( \#m \) and node \( \#n \) in a system that already has \( k \) nodes. (In the example, \( m = 1 \) and \( n = 2 \)).

The equations assuming a circular current of magnitude \( i_L \) are as follows:

\[
\begin{bmatrix}
v_1 \\
v_2 \\
\vdots \\
v_m \\
v_n \\
\vdots \\
v_{k-1} \\
v_k
\end{bmatrix} =
\begin{bmatrix}
z_{1,1} & z_{1,2} & \cdots & \cdots & \cdots \\
z_{2,1} & z_{2,2} \\
\vdots  \\
z_{m,1} & z_{m,2} \\
z_{n,1} & z_{n,2} \\
\vdots  \\
z_{k-1,1} & z_{k-1,2} \\
z_{k,1} & z_{k,2} & \cdots & \cdots & \cdots \\
z_{k,k-1} & z_{k,k} & \cdots & \cdots & \cdots
\end{bmatrix}
\begin{bmatrix}
Z_{k,k-1} & Z_{k,k} \\
Z_{k-1,k} & Z_{k-1,k} \\
\vdots  \\
Z_{m,k} & Z_{m,k} \\
Z_{n,k} & Z_{n,k} \\
\vdots  \\
Z_{1,k} & Z_{1,k}
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
\vdots  \\
i_m + i_L \\
i_n - i_L \\
\vdots  \\
i_{k-1} \\
i_k
\end{bmatrix}
\]

- We can expand the equations as shown on the next slide.
The 4th step in the $Z_{bus}$ building algorithm

- We rewrite the former equation
- We define a new vector, $a$ which represents the difference between columns $m$ and $n$ in the $Z_{bus,old}$ matrix
- Therefore the former equation will be as follows:
- The voltage drop across the new branch, $z_{new}$ will be:

\[
\begin{bmatrix}
v_1 \\
v_2 \\
\vdots \\
v_k \\
\end{bmatrix}
= 
\begin{bmatrix}
z_{1,1} & z_{1,2} & \cdots & z_{1,k} \\
z_{2,1} & z_{2,2} & \cdots & z_{2,k} \\
\vdots & \vdots & \ddots & \vdots \\
z_{k,1} & z_{k,2} & \cdots & z_{k,k} \\
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
\vdots \\
i_k \\
\end{bmatrix}
+ 
\begin{bmatrix}
z_{1m} - z_{1n} \\
z_{2m} - z_{2n} \\
\vdots \\
z_{km} - z_{kn} \\
\end{bmatrix}
\cdot i_L
\]

\[
V_{bus} = Z_{bus,old} \cdot I_{bus} + a \cdot i_L = \begin{bmatrix}
z_{1m} - z_{1n} \\
z_{2m} - z_{2n} \\
\vdots \\
z_{km} - z_{kn} \\
\end{bmatrix}
\]

\[
v_n - v_m = z_{new} \cdot i_L
\]

\[
v_m - v_n + z_{new} \cdot i_L = 0
\]
The 4th step in the $Z_{bus}$ building algorithm

We expand $v_m$ and $v_n$ in the expression: $v_m - v_n + z_{new} \cdot i_L = 0$ \(^{(1)}\)
using lines \#m and \#n from the matrix equation in the last slide.

This expansion gives:

$$v_m = \begin{bmatrix} z_{m1}, & z_{m2}, & \cdots, & z_{mk} \end{bmatrix} \cdot I_{bus} + (z_{mm} - z_{mn}) \cdot i_L$$ and

$$v_n = \begin{bmatrix} z_{n1}, & z_{n2}, & \cdots, & z_{nk} \end{bmatrix} \cdot I_{bus} + (z_{nm} - z_{nn}) \cdot i_L$$

We substitute these into the equation \(^{(1)}\)

which leads to:

$$\begin{bmatrix} z_{n1} - z_{m1}, & \cdots, & z_{nk} - z_{mk} \end{bmatrix} I_{bus} + (2z_{mn} - z_{mm} - z_{nn} - z_{new})i_L = 0$$

This is in compact notation: $0 = bI_{bus} + (2z_{mn} - z_{mm} - z_{nn} - z_{new})i_L$ \(^{(2)}\) where the k-dimensional row matrix $b$ is defined by: $b = \begin{bmatrix} z_{n1} - z_{m1}, & \cdots, & z_{nk} - z_{mk} \end{bmatrix}$ \(^{(3)}\).

The loop current can be solved from equation \(^{(2)}\) and substituted into eq. \(^{(3)}\).
The 4th step in the \( Z_{\text{bus}} \) building algorithm (5)

The result is:  
\[
V_{\text{bus}} = Z_{\text{bus,old}} + \frac{1}{(z_{\text{new}} + z_{\text{mm}} + z_{\text{nn}} - 2z_{\text{mn}})} \cdot abI_{\text{bus}}
\]

which can be written:  
\[
V_{\text{bus}} = \left\{ Z_{\text{bus,old}} + \frac{ab}{(z_{\text{new}} + z_{\text{mm}} + z_{\text{nn}} - 2z_{\text{mn}})} \right\} I_{\text{bus}}
\]

or  
\[
V_{\text{bus}} = Z_{\text{bus,new}} \cdot I_{\text{bus}}
\]

This leads to:  
\[
Z_{\text{bus,new}} = Z_{\text{bus,old}} + \frac{ab}{(z_{\text{new}} + z_{\text{mm}} + z_{\text{nn}} - 2z_{\text{mn}})}
\]

This formula shows how to calculate a new version of the \( Z_{\text{bus}} \) matrix.
Example: $Z_{bus}$ building

In our numerical example: $z_{new} = z_3 = j0.10$ and $Z_{bus,old} = j \begin{bmatrix} 0.15 & 0 & 0 \\ 0 & 0.075 & 0.075 \\ 0 & 0.075 & 0.175 \end{bmatrix}$

is the old $Z$-bus matrix from the 3rd step.

Therefore $z_{mm} = z_{11} = j0.15$ and $z_{nn} = z_{22} = j0.075$

and $2z_{mn} = 2z_{12} = 0$. Therefore $z_{new} + z_{mm} + z_{nn} - 2z_{mn} = j0.3250$

We get $a = j \begin{bmatrix} 0.15 - 0 \\ 0 - 0.075 \\ 0 - 0.075 \end{bmatrix} = j \begin{bmatrix} 0.15 \\ -0.075 \\ -0.075 \end{bmatrix}$

The $b$ matrix will be:

$b = j \begin{bmatrix} 0 - 0.15 & 0.075 - 0 & 0.075 - 0 \end{bmatrix} = j \begin{bmatrix} 0.15 & 0.075 & 0.075 \end{bmatrix}$
Example: $Z_{bus}$ building (2)

\[
\frac{ab}{(z_{new} + z_{mm} + z_{nn} - 2z_{mn})} = \frac{j}{0.3250} \begin{bmatrix} 0.15 \\ -0.075 \\ -0.075 \end{bmatrix} \begin{bmatrix} 0.15 & 0.075 & 0.075 \\ \end{bmatrix}
\]

\[
\begin{bmatrix} -0.0692 & 0.0346 & 0.0346 \\ 0.0346 & -0.0173 & -0.0173 \\ 0.0346 & -0.0173 & -0.0173 \end{bmatrix} = j \begin{bmatrix} -0.0692 & 0.0346 & 0.0346 \\ 0.0346 & -0.0173 & -0.0173 \\ 0.0346 & -0.0173 & -0.0173 \end{bmatrix}
\]

By adding this matrix to $Z_{bus,old}$ we get

\[
Z_{bus,new} = j \begin{bmatrix} 0.0808 & 0.0346 & 0.0346 \\ 0.0346 & 0.0577 & 0.0577 \\ 0.0346 & 0.0577 & 0.1577 \end{bmatrix}
\]
The 5th step in the \( Z_{\text{bus}} \) building algorithm (1)

- We finally in step 5 add a branch \((z_5)\) between 2 previously connected nodes.
- This connects nodes \( m = 1 \) and \( n = 3 \) and is the same kind of step as step #4.
- The new impedance is \( z_5 = z_{\text{new}} \).

\[
z_{\text{new}} = z_5 = j0.1 \quad \text{and} \quad z_{mm} = z_{11} = j0.0808 \quad \text{and} \quad z_{nn} = z_{33} = j0.1577
\]
\[
\text{and} \quad 2z_{mn} = 2z_{13} = j0.0692
\]
\[
\text{Therefore} \quad z_{\text{new}} + z_{mm} + z_{nn} - 2z_{mn} = j0.2693
\]
The 5th step in the $Z_{bus}$ building algorithm (2)

We get $a = j \begin{bmatrix} 0.0808 - 0.0346 \\ 0.0346 - 0.0577 \\ 0.0346 - 0.1577 \end{bmatrix} = j \begin{bmatrix} 0.0462 \\ -0.0231 \\ -0.1231 \end{bmatrix}$ The $b$ matrix will be:

$b = j \begin{bmatrix} 0.0346 - 0.0808 & 0.0577 - 0.0346 & 0.1577 - 0.0346 \end{bmatrix}$

$b = j \begin{bmatrix} -0.0462 & 0.0231 & 0.1231 \end{bmatrix}$

The incremental matrix will be

$$a = \frac{j}{0.2693} \begin{bmatrix} 0.0462 \\ -0.0231 \\ -0.1231 \end{bmatrix} \begin{bmatrix} 0.0462 & 0.0231 & 0.1231 \end{bmatrix}$$

$$= j \begin{bmatrix} -0.0079 & 0.0040 & 0.0211 \\ 0.0040 & -0.0020 & -0.0106 \\ 0.0211 & -0.0106 & -0.0563 \end{bmatrix}$$
The 5th step in the $Z_{\text{bus}}$ building algorithm (3)

By adding this matrix to $Z_{\text{bus,old}}$ we finally get the final version of the $Z_{\text{bus}}$ matrix:

$$Z_{\text{bus,old}} = Z_{\text{bus}} = j \begin{bmatrix} 0.0729 & 0.0386 & 0.0557 \\ 0.0386 & 0.0557 & 0.0471 \\ 0.0557 & 0.0471 & 0.1014 \end{bmatrix}$$

This completes our numerical example.
Transient synchronous machine short circuit currents

- Subtransient, $x''_d$ and transient reactances, $x''_d$ are smaller than the steady state synchronous reactances, $x'_d$
- A DC component is present in all 3 phases
- The exact shape of the short circuit current will depend on the phase instant of the short circuit and is therefore different in the 3 phases
Energy control centers
Energy Control Centers

- **Energy Control Center (ECC):**
  - SCADA, EMS, operational personnel
  - “Heart” (eyes & hands, brains) of the power system

- **Supervisory control & data acquisition (SCADA):**
  - Supervisory control: remote control of field devices
  - Data acquisition: monitoring of field conditions
  - SCADA components:
    - Master Station: System “Nerve Center” located in ECC
    - Remote terminal units: Gathers data at substations; sends to Master Station
    - Communications: Links Master Station with Field Devices

- **Energy management system (EMS):**
  - Topology processor & network configurator
  - State estimator and power flow model development
  - Automatic generation control (AGC), Optimal power flow (OPF)
  - Security assessment and alarm processing
Early Power System Control (in 1919)
Energy Control Centers


Figure 7-1. Components of a typical energy information system.
Landsvirkjun’s Dispatch Centre in Reykjavik was commissioned in 1989. Its role is coordinating operation of the electricity system. Its chief task is to ensure conditions that allow the system to handle variable loads at all times, thereby safeguarding operational security and efficiency. It monitors the entire power system and controls both production of electricity and its transmission nation-wide.

In order to fulfill its role, the Dispatch Centre must have comprehensive hands-on data about the electricity system and therefore needs to be in constant, reliable contact with all its units. The Dispatch Centre is linked to power plants all over Iceland by means of microwave radio and optical fibre cables. These carry an average of 600 status point indications per minute from 35 remote terminals to its control computer, which gives real-time information about each and every part of the system. It sends warnings of any deviations to the two dispatchers who are on duty at any time, and with a complete overview of the electricity system they are able to respond accordingly and prescribe the correct action to be taken, via the remote control system.

Source: http://www.lv.is
Remote terminal unit

Substation

SCADA Master Station

Communication link

Energy control center with EMS

EMS 1-line diagram

EMS alarm display
More energy control centers
The control of distributed generation

Micro-Grid Operation and Control

References
