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APPENDIX B EXPRESSING R_{TIE} IN TERMS OF X_{TIE}

This appendix shows $R_{TIE} = (3/2) \times 0.07463 \times X_{TIE}$ and obtains the equation used to solve X_{TIE}.

B.1 EXPRESSING R_{TIE} IN TERMS OF X_{TIE}

This section shows $\boldsymbol{Z_{TIE}}$ can be computed using:

$$\boldsymbol{Z_{TIE}} = \frac{3}{2} \times 0.07463 \times X_{TIE} + \boldsymbol{j}\ X_{TIE} \tag{B.1}$$

To clarify the fraction 0.07463, we note the tie line is stranded throughout with "Twin Dinosaur". The per kilometre positive sequence line resistance of a typical "Twin Dinosaur" conductor is 0.000015 p.u. and the positive sequence line reactance is 0.000201 p.u. The ratio of resistance to reactance is 0.07463. Hence, if X_{TIE}^{UC} is the line reactance of the uncompensated network, then R_{TIE} can be computed using:

$$R_{TIE} = 0.07463 \times X_{TIE}^{UC} \tag{B.2}$$

Therefore, for the case where the tie line is not series compensated, $\boldsymbol{Z_{TIE}}$ can be computed using:

$$\boldsymbol{Z_{TIE}} = 0.07463 \times X_{TIE}^{UC} + \boldsymbol{j}\ X_{TIE}^{UC}. \tag{B.3}$$

To clarify the fraction $3/2$, we note series capacitors are present in the Grootvlei/Atlas/Tutuka-to-Perseus/Beta network, in the Perseus/Beta-to-Hydra network and in the Hydra-to-Muldersvlei network (Chapter 3, figure 3.3).

Assume X_{TIE} is the line reactance of the series compensated network and assume $X_{TIE} = n \times X_{TIE}^{UC}$. The R to X ratio of the series compensated tie line is:

$$\frac{R_{TIE}}{X_{TIE}} = \frac{R_{TIE}}{n \times X_{TIE}^{UC}}$$

But: $$\frac{R_{TIE}}{X_{TIE}^{UC}} = 0.07463$$

Hence: $$\frac{R_{TIE}}{X_{TIE}} = \frac{1}{n} \times 0.07463$$

But $X_{TIE} = n \times X_{TIE}^{UC}$, hence: $$R_{TIE} = \left(\frac{X_{TIE}^{UC}}{X_{TIE}} \times 0.07463 \right) X_{TIE} \qquad \text{(B.4)}$$

To obtain the ratio X_{TIE}^{UC} / X_{TIE} it is assumed the percentage series compensation applied to the mentioned three networks is the same. This allows us to compute X_{TIE}^{UC} / X_{TIE} by considering only one of the mentioned networks. We chose the Hydra-to-Muldersvlei network.

With the series caps in service, but the line resistance and shunts omitted from the load flow model, X_{TIE} can be computed by using:

$$X_{TIE} = |\boldsymbol{V}_{\boldsymbol{HYDRA4}}||\boldsymbol{V}_{\boldsymbol{MULDR4}}| \frac{\sin \delta_{HM}}{P_{HM}} \qquad \text{(B.5)}$$

Where, $\boldsymbol{V}_{\boldsymbol{HYDRA4}}$ is the voltage vector of the 400 kV Hydra busbar; $\boldsymbol{V}_{\boldsymbol{MULDR4}}$ is the voltage vector of the 400 kV Muldersvlei busbar; δ_{HM} is the power angle by

which $\boldsymbol{V}_{\boldsymbol{HYDRA}4}$ leads $\boldsymbol{V}_{\boldsymbol{MULDR}4}$ and P_{HM} is the power Hydra exports to Muldersvlei.

Equation B.5 can also be used to compute X_{TIE}^{UC}. The proviso is $\left|\boldsymbol{V}_{\boldsymbol{HYDRA}4}\right|$, $\left|\boldsymbol{V}_{\boldsymbol{MULDR}4}\right|$, δ_{HM} and P_{HM} are obtained when the series capacitors in the Hydra-to-Muldersvlei network are out of service.

When the loads, line charging, line resistance, voltage regulating shunts and the series capacitors in the Hydra-to-Muldersvlei section are removed from the detailed network model the load flow shown in figure B.1 is obtained.

For the network shown in figure B.1, we have:

$$\left|\boldsymbol{V}_{\boldsymbol{HYDRA}4}\right| = 0.986 \text{ p.u.} \tag{B.6-a}$$

$$\left|\boldsymbol{V}_{\boldsymbol{MULDR}4}\right| = 1.021 \text{ p.u.} \tag{B.6-b}$$

$$\begin{aligned}\delta_{\boldsymbol{HM}} &= -7.5^{\circ} - \left(-34.8^{\circ}\right) \\ &= 27.3^{\circ}\end{aligned} \tag{B.6-c}$$

$$\begin{aligned}P_{HM} &= \left(298 + 299 + 303\right) \\ &= 900 \text{ MW}\end{aligned} \tag{B.6-d}$$

The substitution of equation B.6 into equation B.5 yields:

$$\begin{aligned}X_{TIE}^{UC} &= \left|\boldsymbol{V}_{\boldsymbol{HYDRA}4}\right|\left|\boldsymbol{V}_{\boldsymbol{MULDR}4}\right| \frac{\sin\delta_{HM}}{P_{HM}} \\ &= 0.986 \times 1.021 \times \frac{\sin\left(27.3^{\circ}\right)}{9} \\ &= 0.05130 \text{ p.u; } S_{BASE} = 100 \text{ MVA}\end{aligned} \tag{B.7}$$

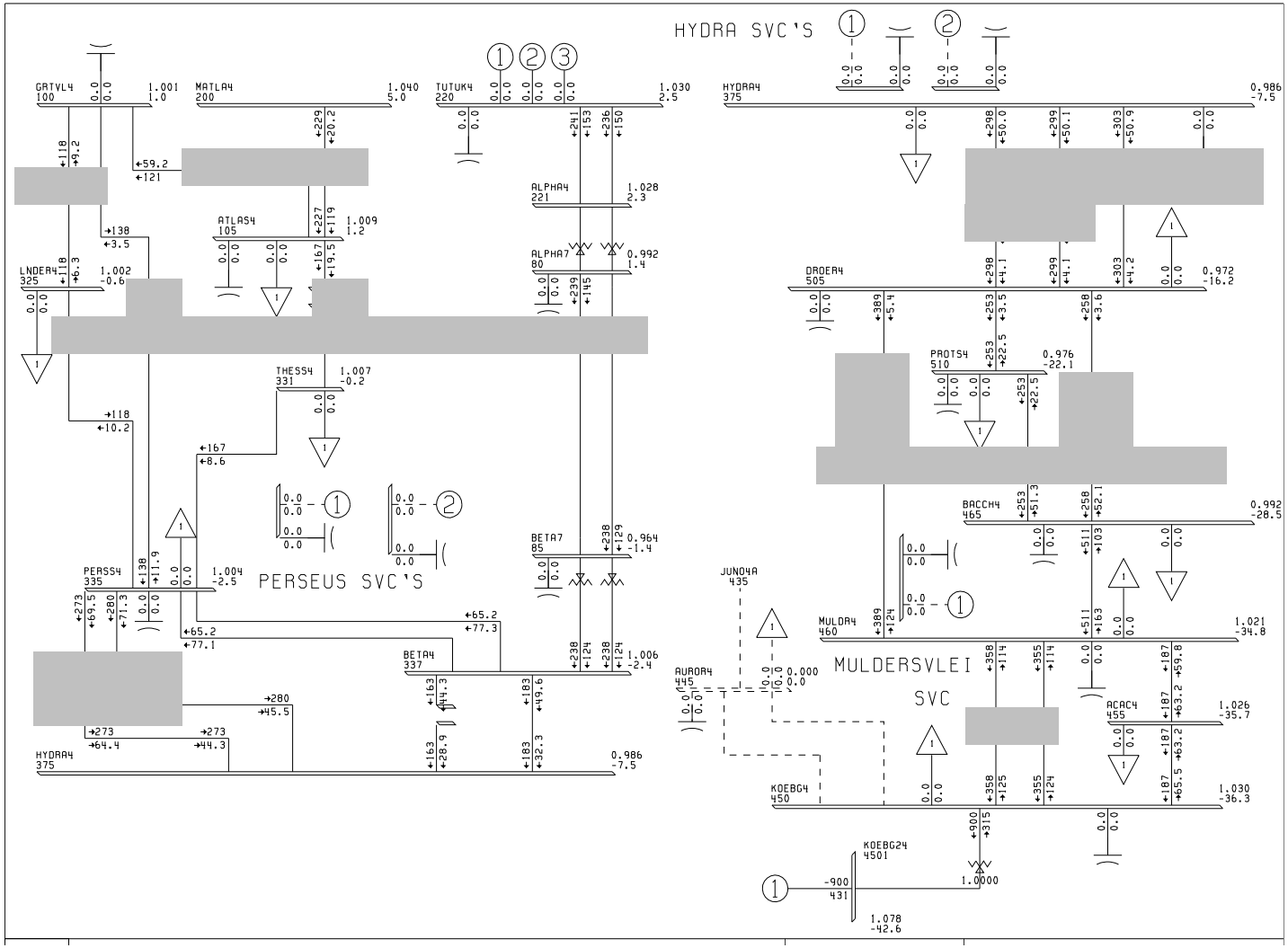


FIGURE B.1 Steady state load flow when the loads, line charging, line resistance and voltage regulating shunts are omitted from the detailed network model shown in figure 3.3. All the series capacitors installed in the Hydra-to-Muldersvlei section are removed

When the Hydra-to-Muldersvlei section operates with the series capacitors in service, we have (figure B.2):

$$\left|\boldsymbol{V}_{\boldsymbol{HYDRA}4}\right| = 1.003 \text{ p.u.} \tag{B.8-a}$$

$$\left|\boldsymbol{V}_{\boldsymbol{MULD}4}\right| = 1.023 \text{ p.u.} \tag{B.8-b}$$

$$\begin{aligned} \delta_{HM} &= -7.4^{\circ} - \left(-24.2^{\circ}\right) \\ &= 16.8^{\circ} \end{aligned} \tag{B.8-c}$$

$$\begin{aligned} P_{HM} &= \left(353 + 354 + 193\right) \\ &= 900 \text{ MW} \end{aligned} \tag{B.8-d}$$

The substitution of equation B.8 into equation B.5 yields:

$$\begin{aligned} X_{TIE} &= \left|\boldsymbol{V}_{\boldsymbol{HYDRA}4}\right|\left|\boldsymbol{V}_{\boldsymbol{MULDR}4}\right| \frac{\sin \delta_{HM}}{P_{HM}} \\ &= 1.003 \times 1.023 \times \frac{\sin\left(16.8^{\circ}\right)}{9.0} \\ &= 0.03295 \text{ p.u; } S_{BASE} = 100 \text{ MVA} \end{aligned} \tag{B.9}$$

The ratio X_{TIE}^{UC} / X_{TIE} is thus equal to:

$$\begin{aligned} \frac{X_{TIE}^{UC}}{X_{TIE}} &= \frac{0.0513}{0.03295} \\ &= 1.5569 \\ &\approx \frac{3}{2} \end{aligned} \tag{B.10}$$

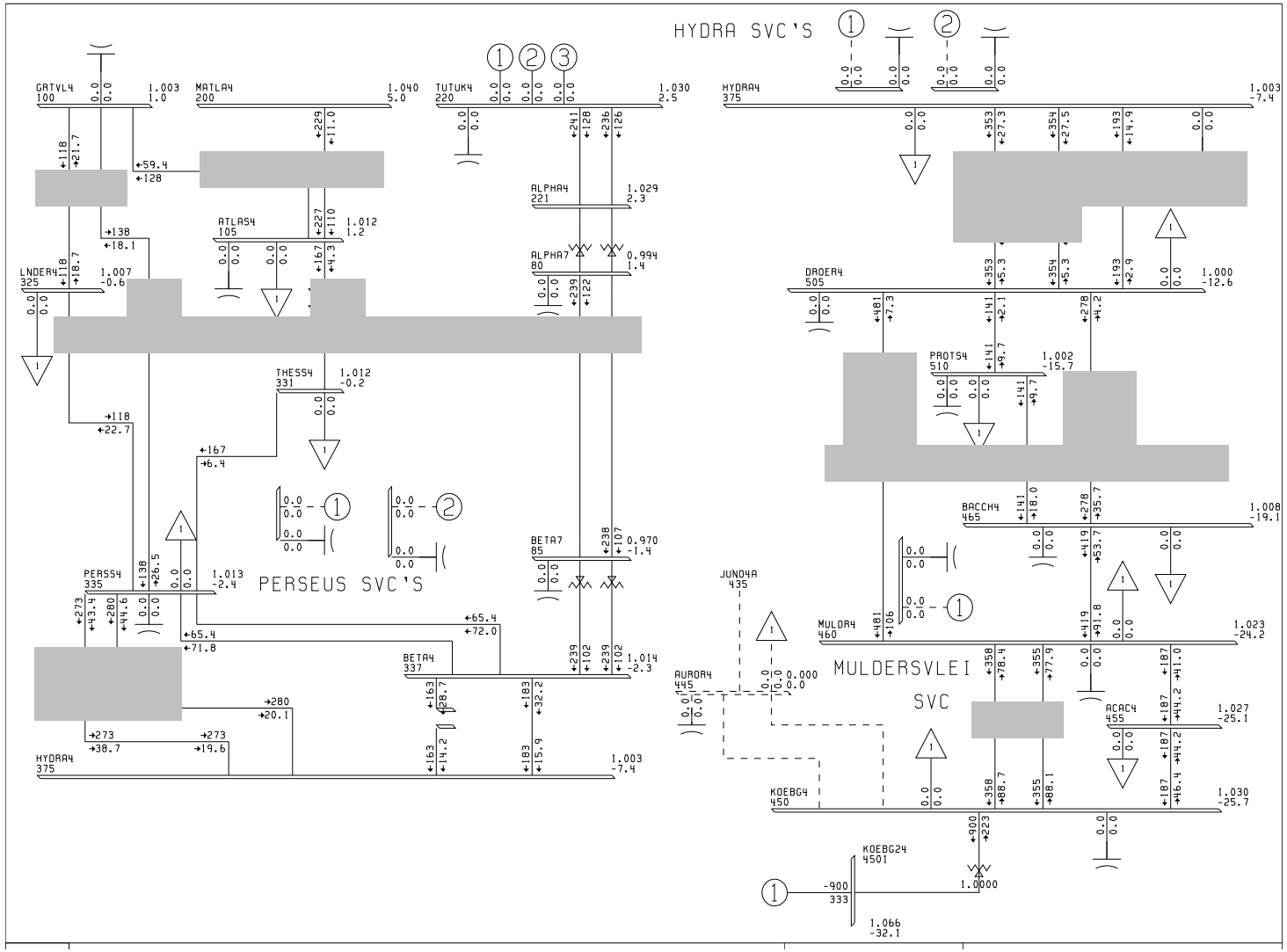


FIGURE B.2 Steady state load flow when the loads, line charging, line resistance and voltage regulating shunts are omitted from the detailed network model shown in figure 3.3

Hence, according to equation B.2 and B.10 we have:

$$R_{TIE} = \frac{3}{2} \times 0.07463 \times X_{TIE} \tag{B.11}$$

B.2 EQUATION USED TO COMPUTE X_{TIE}

Assume P_{EXP} is the power Perseus/Beta exports to Hydra in the simplified network model shown in figure 3.8 of Chapter 3.

X_{TIE} is solved to yield a $\boldsymbol{Z_{TIE}} = (3/2) \times 0.07463 \times X_{TIE} + \boldsymbol{j}\ X_{TIE}$ that ensures Perseus/Beta exports P_{EXP} MW to Hydra in the improved two generator model shown in figure 3.2 of Chapter 3.

To simplify the equation used to compute P_{EXP} we replace the Mpumalanga-to-Perseus network and the Muldersvlei-to-Koeberg network with their Thevenin equivalent circuits. The network obtained is shown in figure B.3.

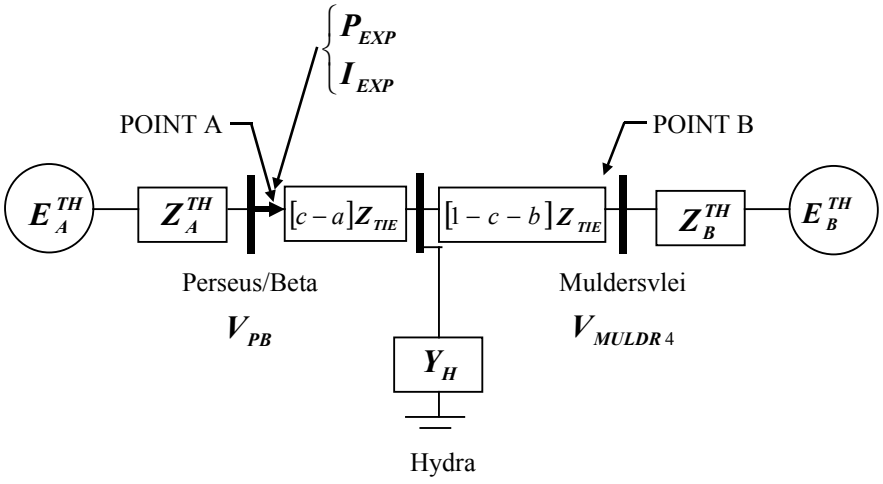


FIGURE B.3 Simplified network of the improved two generator model

A description of all the parameters and vectors, except those listed below, used to define the network shown in figure B.3 is given in Chapter 3, section 3.4. We note $\boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}}$ is the Thevenin voltage and $\boldsymbol{Z}_{\boldsymbol{A}}^{\boldsymbol{TH}}$ is the Thevenin impedance at the Perseus/Beta busbar; $\boldsymbol{E}_{\boldsymbol{B}}^{\boldsymbol{TH}}$ is the Thevenin voltage and $\boldsymbol{Z}_{\boldsymbol{B}}^{\boldsymbol{TH}}$ is the Thevenin impedance at Muldersvlei, and $\boldsymbol{Y}_{\boldsymbol{H}}$ is the admittance of the shunt representing the Hydra load centre.

The admittance $\boldsymbol{Y}_{\boldsymbol{H}} = 1/\boldsymbol{Z}_{\boldsymbol{H}}$ can be computed using:

$$\boldsymbol{Y}_{\boldsymbol{H}} = \frac{\boldsymbol{S}_{\boldsymbol{H}}^{*}}{\left|\boldsymbol{V}_{\boldsymbol{HYDRA4}}\right|^{2}}$$

$$= (P_H - \boldsymbol{j}\, Q_H) / \left|\boldsymbol{V}_{\boldsymbol{HYDRA4}}\right|^{2} \qquad \text{(B.12)}$$

Where, $\boldsymbol{V}_{\boldsymbol{HYDRA4}}$ is the voltage vector of the 400 kV Hydra busbar; P_H is the MW demand and Q_H the MVAR demand of the Hydra load.

P_{EXP} can be computed using:

$$P_{EXP} = \text{Real}\,(\boldsymbol{V}_{\boldsymbol{PB}} \boldsymbol{I}_{\boldsymbol{EXP}}^{*}) \qquad \text{(B.13)}$$

According to figure B.3 $\boldsymbol{V}_{\boldsymbol{PB}}$ can be computed using:

$$\boldsymbol{V}_{\boldsymbol{PB}} = \boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}} - \boldsymbol{I}_{\boldsymbol{EXP}} \boldsymbol{Z}_{\boldsymbol{A}}^{\boldsymbol{TH}} \qquad \text{(B.14)}$$

The substitution of equation B.14 into equation B.13 yields:

$$P_{EXP} = \text{Real}\,(\boldsymbol{V}_{\boldsymbol{PB}} \boldsymbol{I}_{\boldsymbol{EXP}}^{*}) = \text{Real}\,\left[\left(\boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}} - \boldsymbol{I}_{\boldsymbol{EXP}} \boldsymbol{Z}_{\boldsymbol{A}}^{\boldsymbol{TH}}\right) \boldsymbol{I}_{\boldsymbol{EXP}}^{*}\right] \qquad \text{(B.15)}$$

The remainder of this section derives the formulas that can be used to compute E_A^{TH}; E_B^{TH} and I_{EXP}.

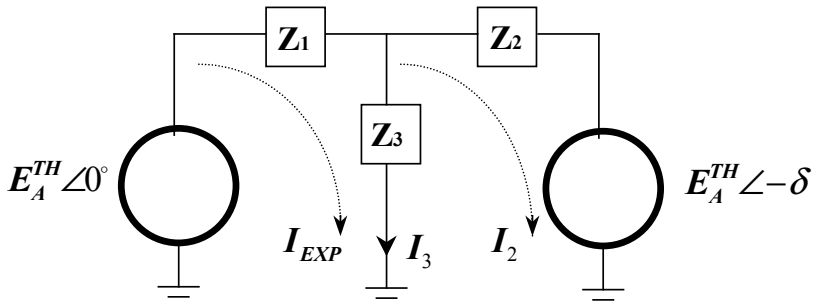


FIGURE B.4 Reducing the improved two generator model into a T network

We define:

$$Z_1 = Z_A^{TH} + (c-a)\, Z_{tie} \qquad \text{(B.16-a)}$$

$$Z_2 = Z_B^{TH} + (1-c-b)\, Z_{tie} \qquad \text{(B.16-b)}$$

$$Z_3 = Z_H = \frac{1}{Y_H} \qquad \text{(B.16-c)}$$

The above definitions reduce the network shown in figure B.3 into the network shown in figure B.4.

When applying Kirchhoff's current law to the network shown in figure B.4 we obtain:

$$I_{EXP} = I_3 + I_2 \qquad \text{(B.17-a)}$$

$$I_3 = I_{EXP} - I_2 \qquad \text{(B.17-b)}$$

When applying Kirchhoff's voltage law we obtain:

$$\boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}} = \boldsymbol{I}_{\boldsymbol{EXP}}\boldsymbol{Z}_1 + (\boldsymbol{I}_1 - \boldsymbol{I}_2)\boldsymbol{Z}_3$$

$$= \boldsymbol{I}_{\boldsymbol{EXP}}(\boldsymbol{Z}_1 + \boldsymbol{Z}_3) - \boldsymbol{I}_2\boldsymbol{Z}_3 \qquad \text{(B.18-a)}$$

$$-\boldsymbol{E}_{\boldsymbol{B}}^{\boldsymbol{TH}} = \boldsymbol{I}_2\boldsymbol{Z}_2 + (\boldsymbol{I}_2 - \boldsymbol{I}_{\boldsymbol{EXP}})\boldsymbol{Z}_3$$

$$= \boldsymbol{I}_2(\boldsymbol{Z}_2 + \boldsymbol{Z}_3) - \boldsymbol{I}_{\boldsymbol{EXP}}\boldsymbol{Z}_3 \qquad \text{(B.18-b)}$$

In matrix format:

$$\begin{bmatrix} (\boldsymbol{Z}_1 + \boldsymbol{Z}_3) & -\boldsymbol{Z}_3 \\ -\boldsymbol{Z}_3 & (\boldsymbol{Z}_2 + \boldsymbol{Z}_3) \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_{\boldsymbol{EXP}} \\ \boldsymbol{I}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}} \\ -\boldsymbol{E}_{\boldsymbol{B}}^{\boldsymbol{TH}} \end{bmatrix} \qquad \text{(B.19)}$$

This matrix equation should be expressed as follows so that Cramer's rule can be used:

$$[\boldsymbol{A}_1; \boldsymbol{A}_2]\boldsymbol{x} = \boldsymbol{b} \qquad \text{(B.20)}$$

Entry x_i of vector $\boldsymbol{x}$ can, according to Cramer, be solved using:

$$x_i = \frac{\det(B_i)}{\det(A)} \qquad \text{(B.21)}$$

Hence:

$$\boldsymbol{B}_1 = [\boldsymbol{b}, \boldsymbol{A}_2] = \begin{bmatrix} \boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}} & -\boldsymbol{Z}_3 \\ -\boldsymbol{E}_{\boldsymbol{B}}^{\boldsymbol{TH}} & (\boldsymbol{Z}_2 + \boldsymbol{Z}_3) \end{bmatrix}$$

$$\det(\boldsymbol{B}_1) = \boldsymbol{E}_{\boldsymbol{A}}^{\boldsymbol{TH}}(\boldsymbol{Z}_2 + \boldsymbol{Z}_3) - \boldsymbol{E}_{\boldsymbol{B}}^{\boldsymbol{TH}}\boldsymbol{Z}_3 \qquad \text{(B.22-a)}$$

$$\det(\boldsymbol{A}) = (\boldsymbol{Z}_1 + \boldsymbol{Z}_3)(\boldsymbol{Z}_2 + \boldsymbol{Z}_3) - \boldsymbol{Z}_3^2$$

$$= \boldsymbol{Z}_1\boldsymbol{Z}_2 + \boldsymbol{Z}_1\boldsymbol{Z}_3 + \boldsymbol{Z}_2\boldsymbol{Z}_3 \qquad \text{(B.22-b)}$$

The substitution of equation B.22 into equation B.21 yields:

$$\boldsymbol{I}_{EXP} = \frac{\boldsymbol{E}_A^{TH}\left(\boldsymbol{Z}_2 + \boldsymbol{Z}_3\right) - \boldsymbol{E}_B^{TH}\boldsymbol{Z}_3}{\boldsymbol{Z}_1\boldsymbol{Z}_2 + \boldsymbol{Z}_1\boldsymbol{Z}_3 + \boldsymbol{Z}_2\boldsymbol{Z}_3}$$

$$= \frac{\boldsymbol{E}_A^{TH}\left(\boldsymbol{Z}_2/\boldsymbol{Z}_3 + 1\right) - \boldsymbol{E}_B^{TH}}{\boldsymbol{Z}_1\boldsymbol{Z}_2/\boldsymbol{Z}_3 + \boldsymbol{Z}_1 + \boldsymbol{Z}_2} \qquad \text{(B.23)}$$

The Thevenin voltage and impedance, $\boldsymbol{E}_A^{TH}$ and $\boldsymbol{Z}_A^{TH}$, obtained at Point A of the network shown in figure B.3 can be computed using:

$$\boldsymbol{Z}_A^{TH} = \boldsymbol{Z}_P \,//\left[\boldsymbol{j}\left(x'_{MPU} + X_{MPU}^{TRFR} + \boldsymbol{Z}_{LINK}\right) + a\ \boldsymbol{Z}_{TIE}\right]$$

$$= \boldsymbol{A}_1/\boldsymbol{A}_2$$

Where: $$\boldsymbol{A}_1 = \boldsymbol{Z}_P \times \left[\boldsymbol{j}\left(x'_{MPU} + X_{MPU}^{TRFR} + \boldsymbol{Z}_{LINK}\right) + a\ \boldsymbol{Z}_{TIE}\right] \qquad \text{(B.24-a)}$$

$$\boldsymbol{A}_2 = \boldsymbol{Z}_P + \left[\boldsymbol{j}\left(x'_{MPU} + X_{MPU}^{TRFR} + \boldsymbol{Z}_{LINK}\right) + a\ \boldsymbol{Z}_{TIE}\right] \qquad \text{(B.24-b)}$$

$$\boldsymbol{E}_A^{TH} = \boldsymbol{B}_1/\boldsymbol{B}_2$$

Where: $$\boldsymbol{B}_1 = \boldsymbol{E}'_{MUP}\boldsymbol{Z}_P \qquad \text{(B.24-c)}$$

$$\boldsymbol{B}_2 = \boldsymbol{Z}_P + \left[\boldsymbol{j}\left(x'_{MPU} + X_{MPU}^{TRFR} + \boldsymbol{Z}_{LINK}\right) + a\ \boldsymbol{Z}_{TIE}\right] \qquad \text{(B.24-d)}$$

$\boldsymbol{Y}_P = 1/\boldsymbol{Z}_P$ is the admittance of the Perseus load centre.

The Thevenin voltage and impedance, $\boldsymbol{E}_B^{TH}$ and $\boldsymbol{Z}_B^{TH}$, obtained at Point B of the network shown in figure B.3 can be computed using:

$$\boldsymbol{Z}_B^{TH} = \boldsymbol{Z}_M \,//\left[\boldsymbol{j}\left(x'_{KBG} + X_{KBG}^{TRFR}\right) + b\ \boldsymbol{Z}_{TIE}\right]$$

$$= \boldsymbol{C}_1 / \boldsymbol{C}_2$$

Where:

$$\boldsymbol{C}_1 = \boldsymbol{Z_M} \times [\boldsymbol{j}\,(x'_{KBG} + X^{TRFR}_{KBG}) + b\ \boldsymbol{Z_{TIE}}] \quad \text{(B.25-a)}$$

$$\boldsymbol{C}_2 = \boldsymbol{Z_M} + [\boldsymbol{j}\,(x'_{KBG} + X^{TRFR}_{KBG}) + b\ \boldsymbol{Z_{TIE}}] \quad \text{(B.25-b)}$$

$$\boldsymbol{E}^{\boldsymbol{TH}}_{\boldsymbol{B}} = \boldsymbol{D}_1 / \boldsymbol{D}_2$$

Where:

$$\boldsymbol{D}_1 = \boldsymbol{E}'_{\boldsymbol{KBG}} \boldsymbol{Z_M} \quad \text{(B.25-c)}$$

$$\boldsymbol{D}_2 = \boldsymbol{Z_M} + [\boldsymbol{j}\,(x'_{KBG} + X^{TRFR}_{KBG}) + b\ \boldsymbol{Z_{TIE}}] \quad \text{(B.25-d)}$$

$\boldsymbol{Y_M} = 1/\boldsymbol{Z_M}$ is the admittance of the Muldersvlei load centre.

The tie line links the 400 kV Grootvlei/Atlas/Tutuka busbar to the 400 kV Koeberg busbar. Hence, the section of the detailed network model (Chapter 3, figure 3.3) we need to solve does not start at $\boldsymbol{E}'_{\boldsymbol{MPU}}$ nor does it end at $\boldsymbol{E}'_{\boldsymbol{KBG}}$. It starts at $\boldsymbol{V_{MPU}}$ and ends at $\boldsymbol{V_{KOEBG4}}$ (Chapter 3, figure 3.2).

To compel equation B.15 to consider only the Grootvlei/Atlas/Tutuka-to-Koeberg tie line, we set $x'_{MPU} = X^{TRFR}_{MPU} = x'_{KBG} = X^{TRFR}_{KBG} = \boldsymbol{Z_{LINK}} = 0$, $\delta = \boldsymbol{\delta_{POOL}}$, $|\boldsymbol{E}'_{\boldsymbol{MPU}}| = |\boldsymbol{V_{MPU}}|$ and $|\boldsymbol{E}'_{\boldsymbol{KBG}}| = |\boldsymbol{V_{KOEBG4}}|$.

The approach where only the network between V_{MPU} and V_{KOEBG4} is considered is achieved mathematically by setting x'_{MPU}, X^{TRFR}_{MPU}, $\boldsymbol{Z_{LINK}}$, x'_{KBG} and X^{TRFR}_{KBG} to zero in equation B.24 and equation B.25. These equations then simplify to:

$$\boldsymbol{Z}^{\boldsymbol{TH}}_{\boldsymbol{A}} = \boldsymbol{Z_P} // [\boldsymbol{j}\,(x'_{MPU} + X^{TRFR}_{MPU} + \boldsymbol{Z_{LINK}}) + a\ \boldsymbol{Z_{TIE}}]$$

$$= \boldsymbol{Z_P} // (a\ Z_{TIE}) \quad \text{(B.26-a)}$$

$$\boldsymbol{E}^{\boldsymbol{TH}}_{\boldsymbol{A}} = \boldsymbol{E}'_{\boldsymbol{MUP}} \boldsymbol{Z_P} / (\boldsymbol{Z_P} + [\boldsymbol{j}\,(x'_{MPU} + X^{TRFR}_{MPU} + \boldsymbol{Z_{LINK}}) + a\ \boldsymbol{Z_{TIE}}])$$

$$= \boldsymbol{V}_{\boldsymbol{MPU}} \boldsymbol{Z}_{\boldsymbol{P}} / \left(\boldsymbol{Z}_{\boldsymbol{P}} + a \ \boldsymbol{Z}_{\boldsymbol{TIE}} \right) \tag{B.26-b}$$

$$\boldsymbol{Z}_{\boldsymbol{B}}^{\boldsymbol{TH}} = \boldsymbol{Z}_{\boldsymbol{M}} // \left[\boldsymbol{j} \left(x'_{KBG} + X_{KBG}^{TRFR} \right) + b \ \boldsymbol{Z}_{\boldsymbol{TIE}} \right]$$

$$= \boldsymbol{Z}_{\boldsymbol{M}} // \left(b \ \boldsymbol{Z}_{\boldsymbol{TIE}} \right) \tag{B.26-a}$$

$$\boldsymbol{E}_{\boldsymbol{B}}^{\boldsymbol{TH}} = \boldsymbol{E}'_{\boldsymbol{KBG}} \boldsymbol{Z}_{\boldsymbol{M}} / \left(\boldsymbol{Z}_{\boldsymbol{M}} + \left[\boldsymbol{j} \left(x'_{KBG} + X_{KBG}^{TRFR} \right) + b \ \boldsymbol{Z}_{\boldsymbol{TIE}} \right] \right)$$

$$= \boldsymbol{V}_{\boldsymbol{KOEBG4}} \boldsymbol{Z}_{\boldsymbol{M}} / \left(\boldsymbol{Z}_{\boldsymbol{M}} + b \ \boldsymbol{Z}_{\boldsymbol{TIE}} \right) \tag{B.26-b}$$