Signal Processing On A Shrinking Supply

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Mixed Analog-Digital VLSI Circuits and Systems Lab

- **Research focus**: Low-voltage/low-power analog and mixed-signal circuit design
- **Current M.S./Ph.D. students**:
  Abhishek Kammula, Sunitha Bandla, Eric McDonald, Kofi Odame, Sheng-Yu Peng
- **Former M.S./Ph.D. students**:
  Karan Mathur, Mark Neidengard, Yuan Yang
- **Current projects**:
  - High-level synthesis of translinear and log-domain circuits and systems
  - Floating-gate MOS (FGMOS) circuit design
  - Double-gate MOS (DGMOS) modeling and circuit design
  - Chemical sensing with chemoreceiptive neuron MOS (CνMOS) transistors
  - Electrochemical camera: amperometric study of exocytocis

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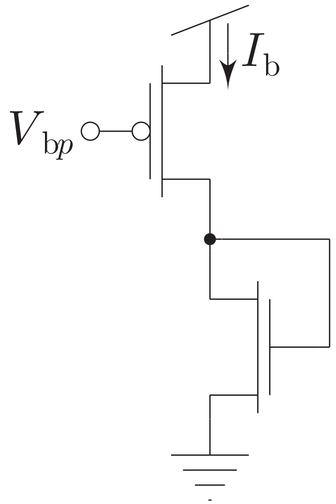
Low Voltage: How Low Can We Go?



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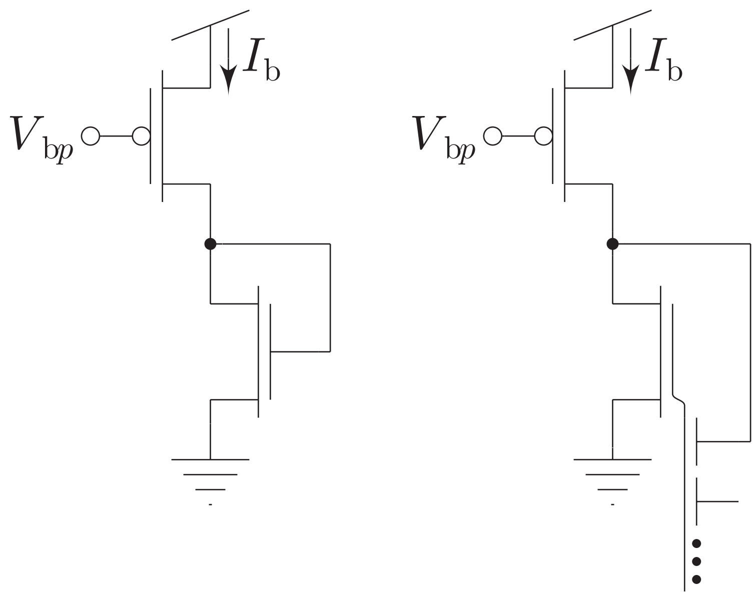

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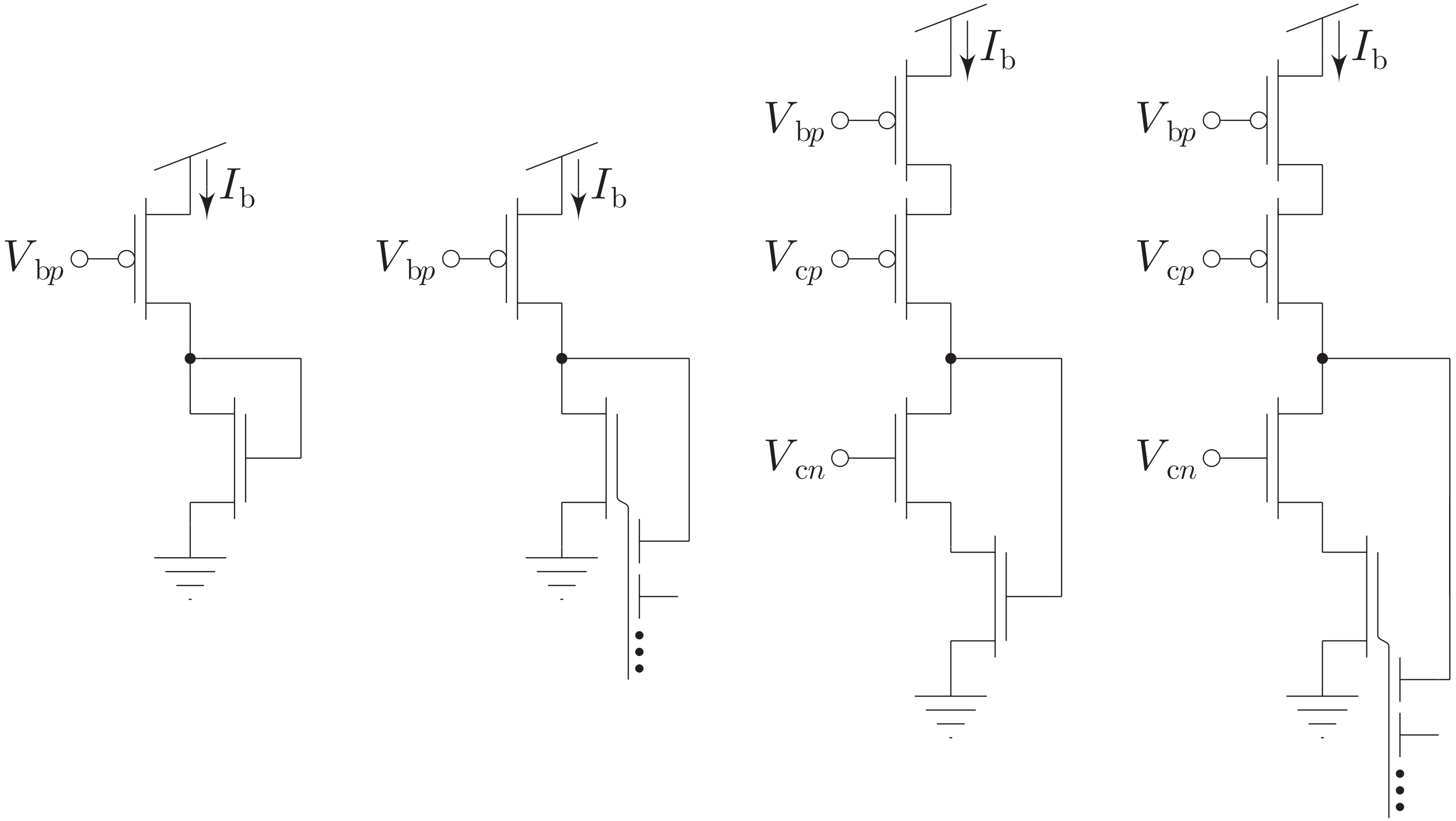
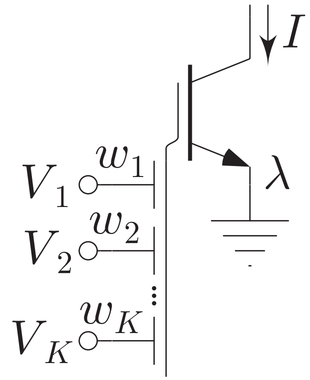


The Ideal Multiple-Input Translinear Element

The ideal multiple-input translinear element (MITE) produces an output current given by

$$I = \lambda I_{\mathrm{s}} e^{(w_1 V_1 + \cdots + w_K V_K)/U_{\mathrm{T}}}$$



where

I_{s}	pre-exponential scaling current
λ	dimensionless constant scaling I_{s} proportionally
V_k	kth control-gate voltage
w_k	dimensionless positive weight scaling V_k
U_{T}	thermal voltage, kT/q.

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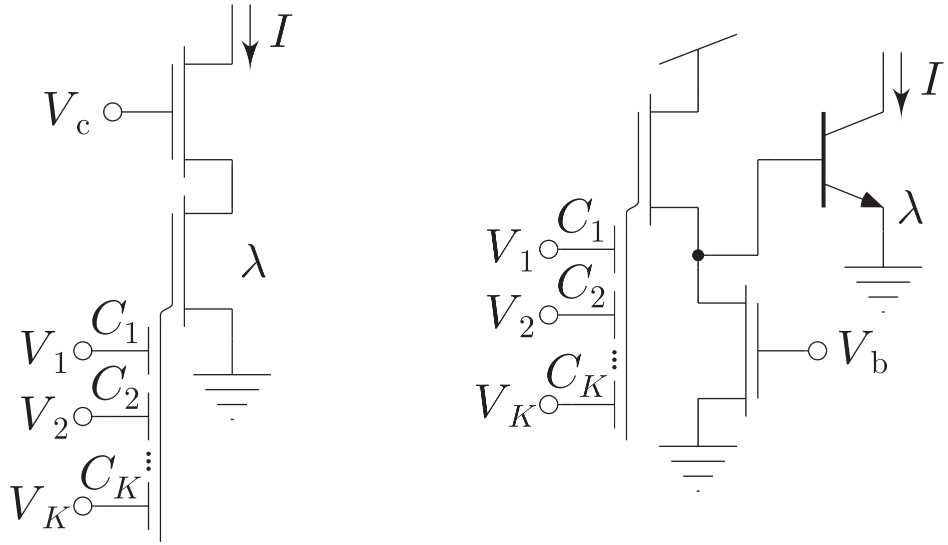
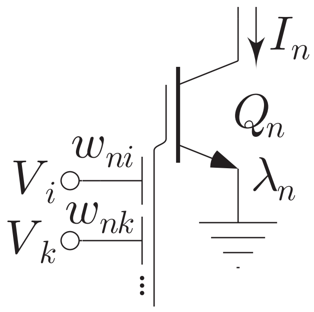
Practical Floating-Gate MITE Implementations



Basic MITE Circuit Stages



$$I_n \propto e^{w_{ni} V_i / U_{\mathrm{T}}} e^{w_{nk} V_k / U_{\mathrm{T}}}$$

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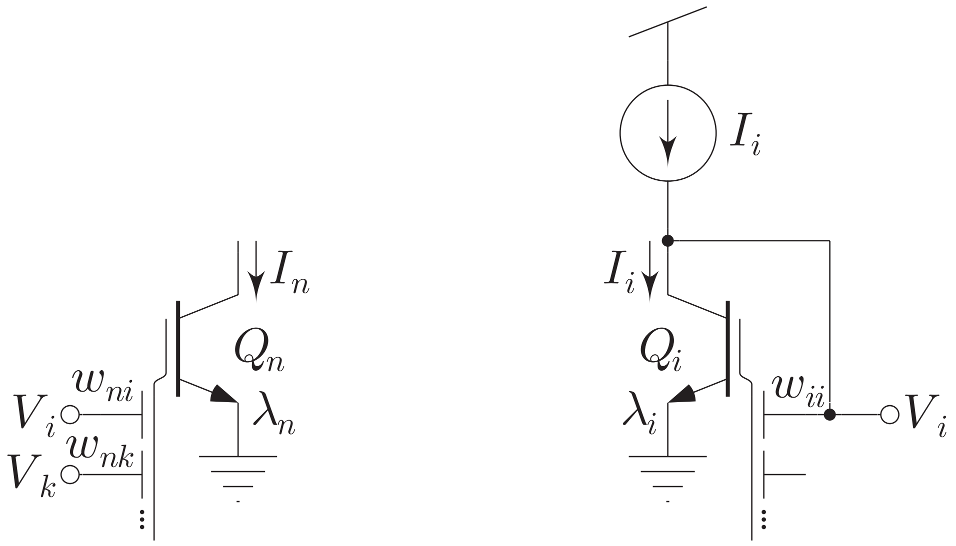

$$I_n \propto e^{w_{ni} V_i / U_\mathrm{T}} e^{w_{nk} V_k / U_\mathrm{T}} \qquad V_i = \frac{U_\mathrm{T}}{w_{ii}} \log I_i - \cdots$$

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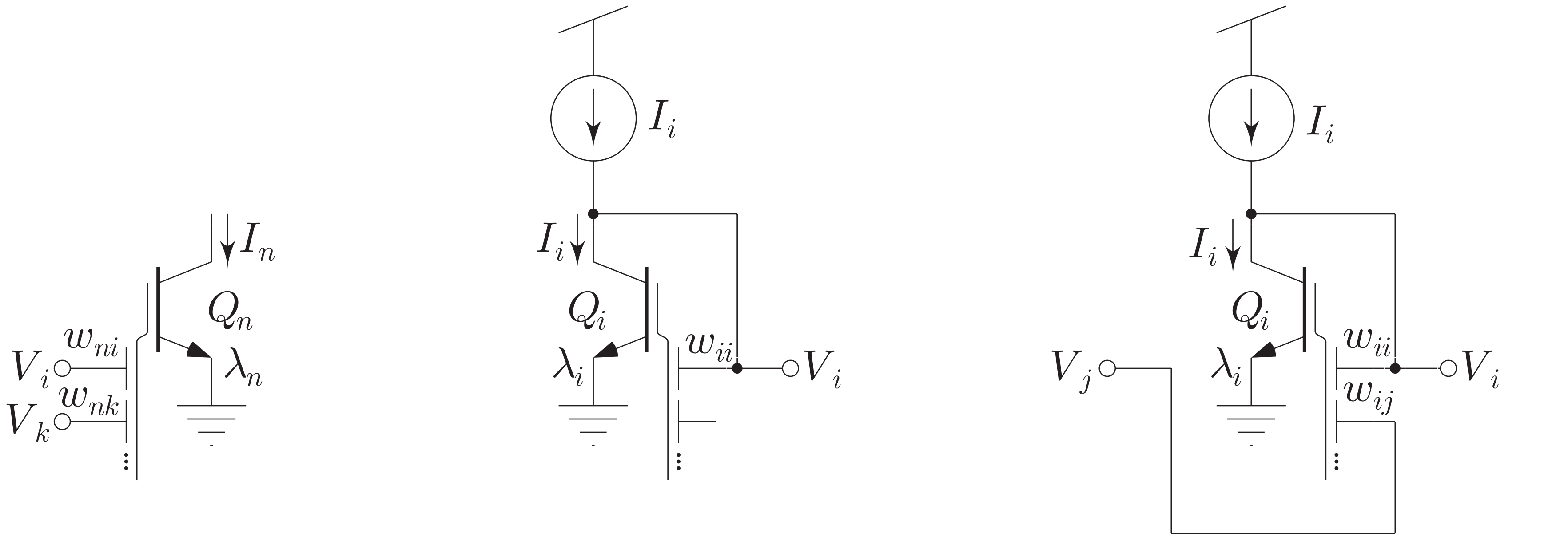

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Elementary MITE Networks

$$I_n \propto e^{w_{ni} V_i / U_\mathrm{T}} e^{w_{nk} V_k / U_\mathrm{T}}$$

$$\Longrightarrow I_n \propto \exp\left(\frac{w_{ni}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{ii}} \log I_i - \cdots\right)\right)$$

$$\times \exp\left(\frac{w_{nk}}{U_\mathrm{T}}\left(\frac{U_\mathrm{T}}{w_{kk}} \log I_k - \cdots\right)\right)$$

$$\Longrightarrow I_n \propto e^{(w_{ni}/w_{ii}) \log I_i} e^{(w_{nk}/w_{kk}) \log I_k}$$

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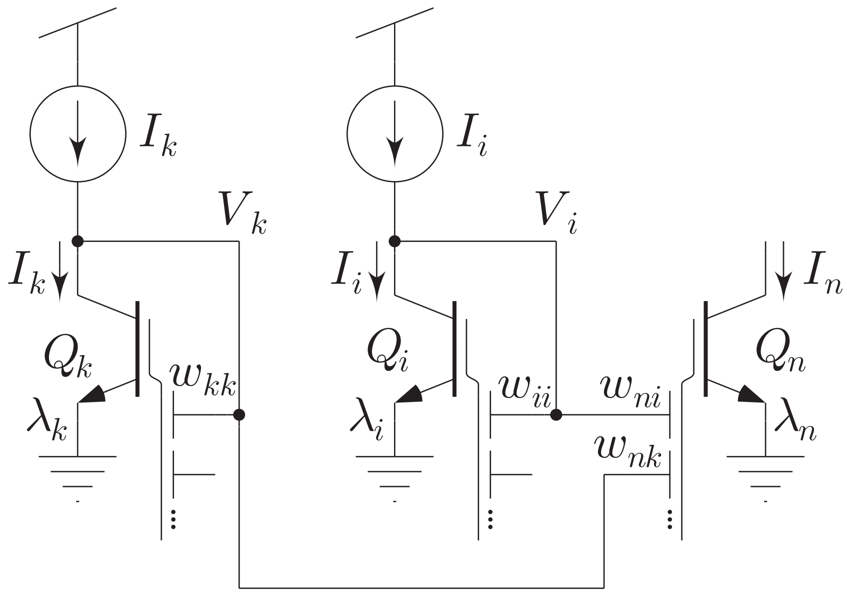

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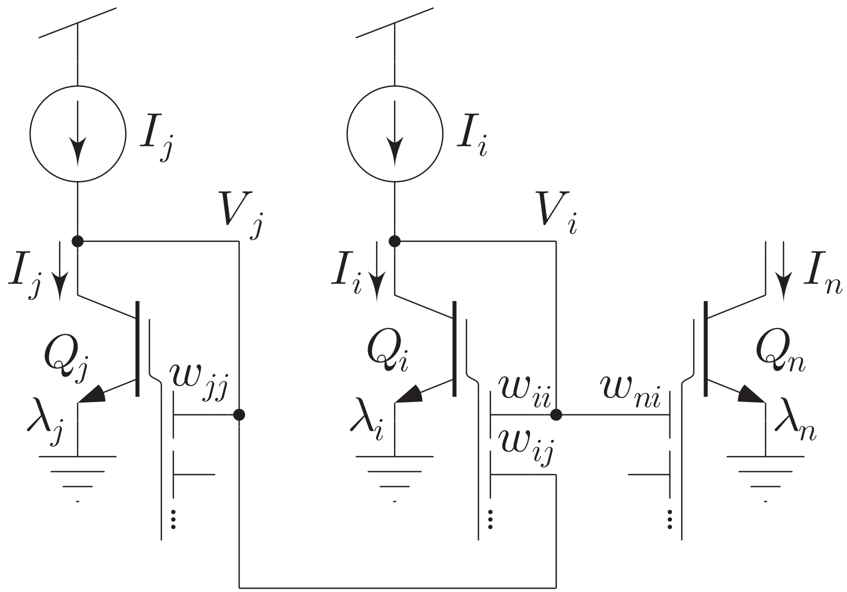
$$\Longrightarrow I_n \propto e^{(w_{ni}/w_{ii}) \log I_i} e^{-\left(w_{ni} w_{ij} / w_{ii} w_{jj}\right) \log I_j}$$

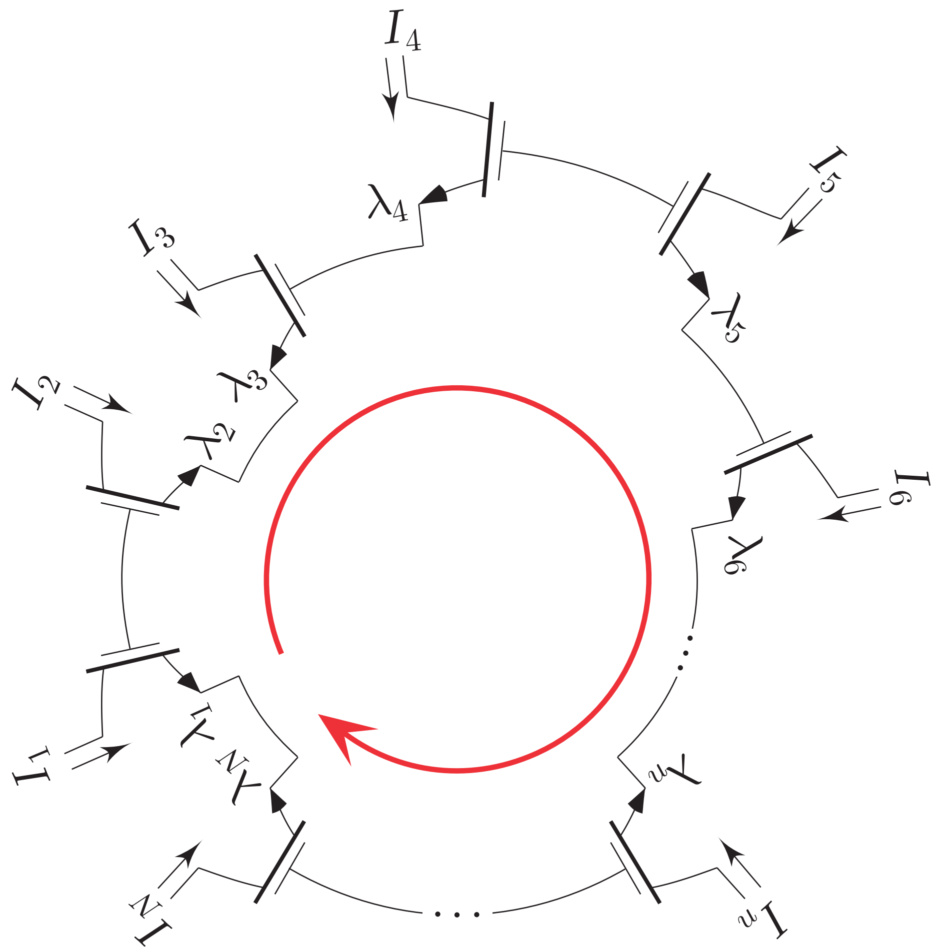
$$\Longrightarrow I_n \propto \frac{I_i^{w_{ni}/w_{ii}}}{I_j^{w_{ni} w_{ij} / w_{ii} w_{jj}}}$$



The Translinear Principle

In a closed loop of junctions comprising an equal number of clockwise and counterclockwise elements, the product of the current densities flowing through the counterclockwise elements is equal to the product of the current densities flowing through the clockwise elements.

$$\prod_{n \in \mathrm{CW}} \frac{I_n}{\lambda_n} = \prod_{n \in \mathrm{CCW}} \frac{I_n}{\lambda_n}$$



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Static MITE Network Synthesis: Square-Root Circuit

Synthesize a square-root circuit described by

$$z = \sqrt{x}, \quad \text{where} \quad x > 0.$$

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$$\frac{I_z}{I_1} = \sqrt{\frac{I_x}{I_1}} \quad \Longrightarrow \quad I_z = \sqrt{I_x I_1} \quad \Longrightarrow \quad I_z^2 = I_x I_1.$$

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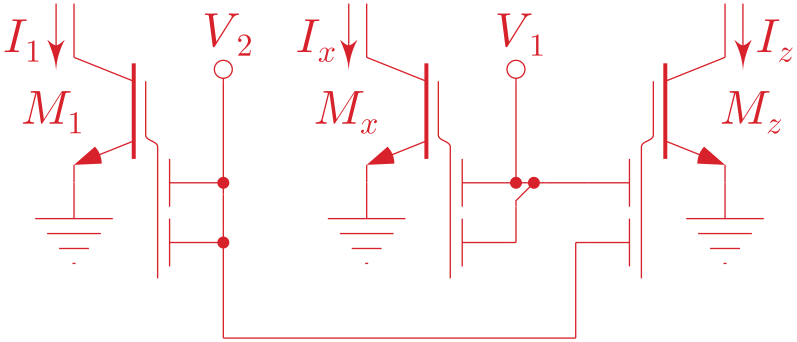

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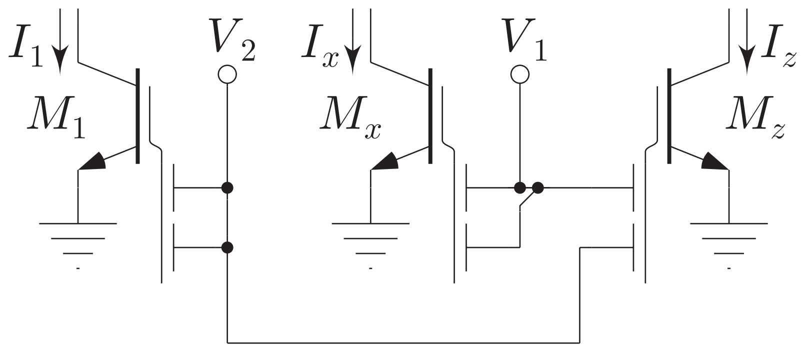

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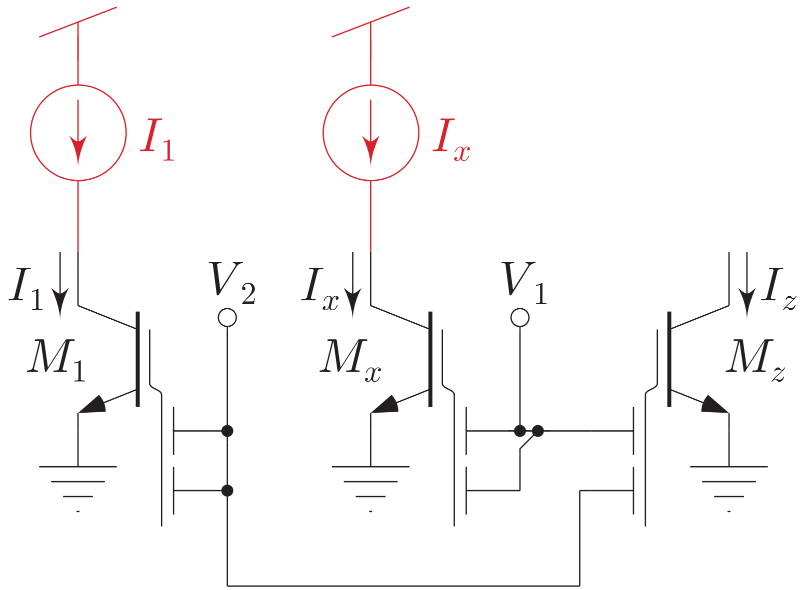

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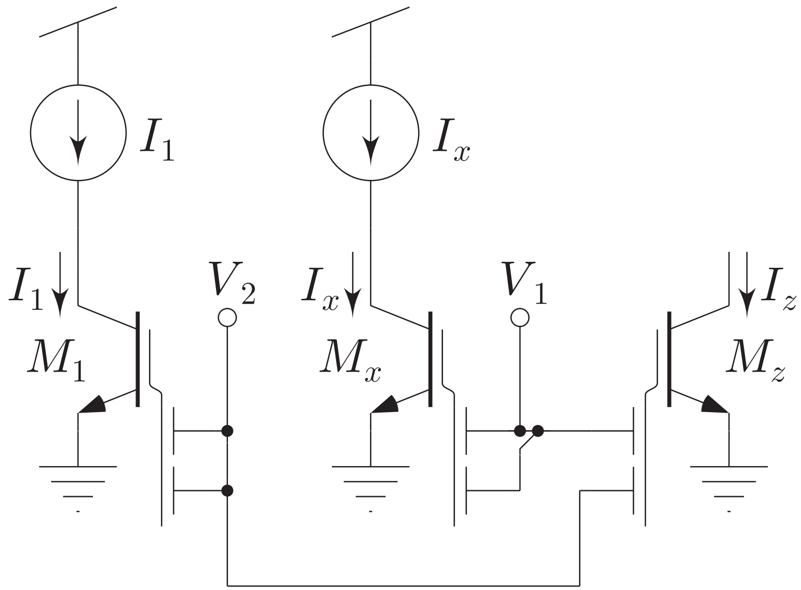

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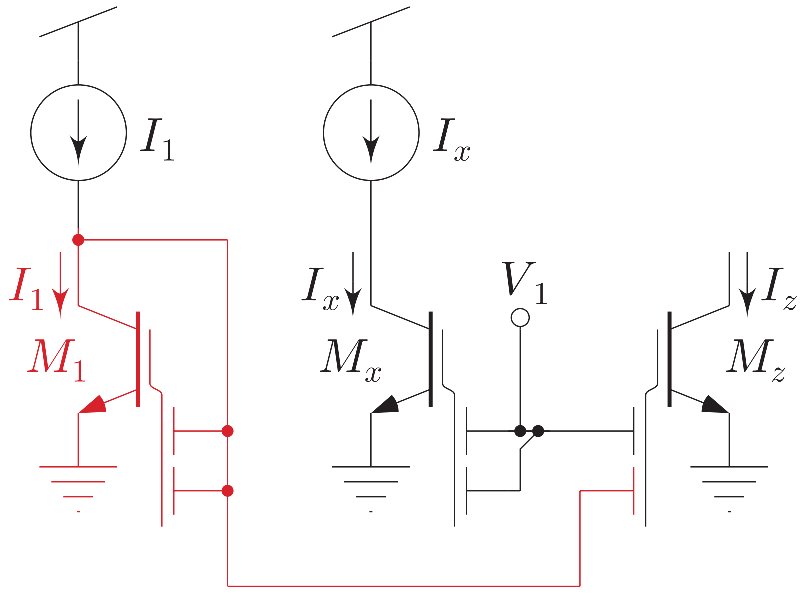

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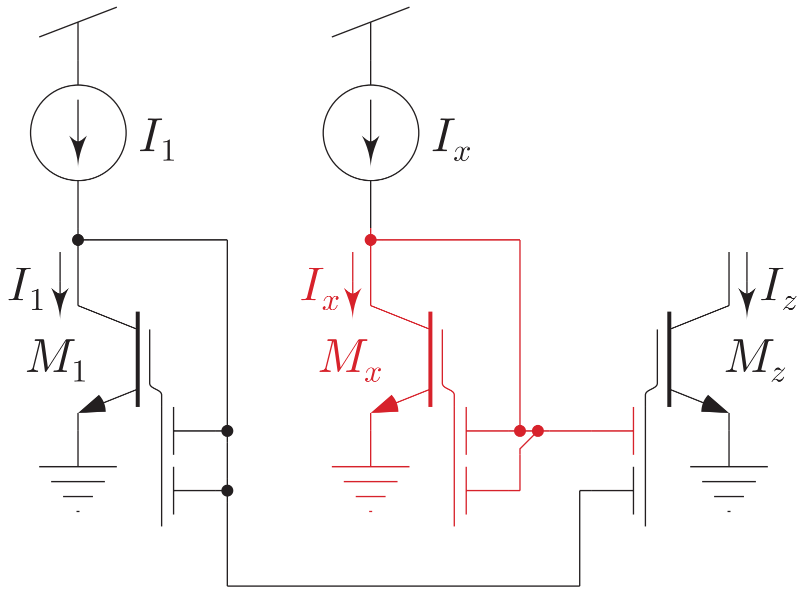

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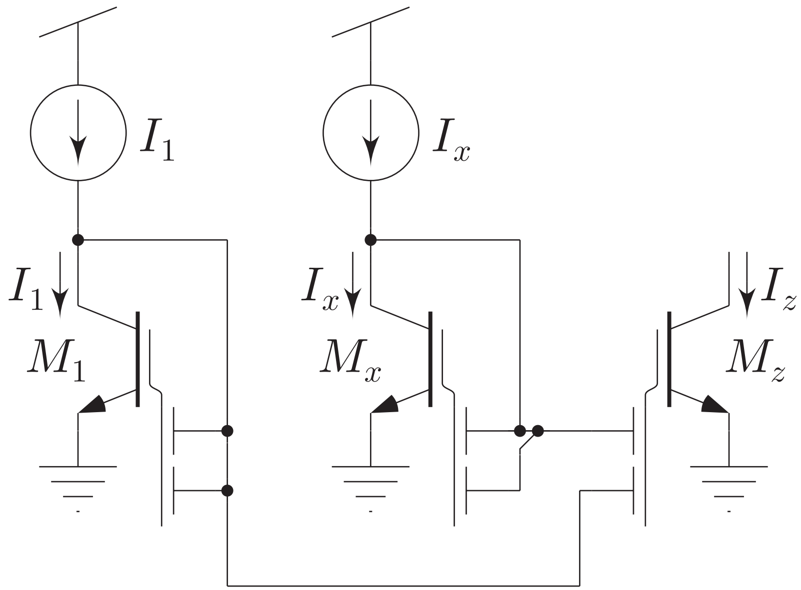

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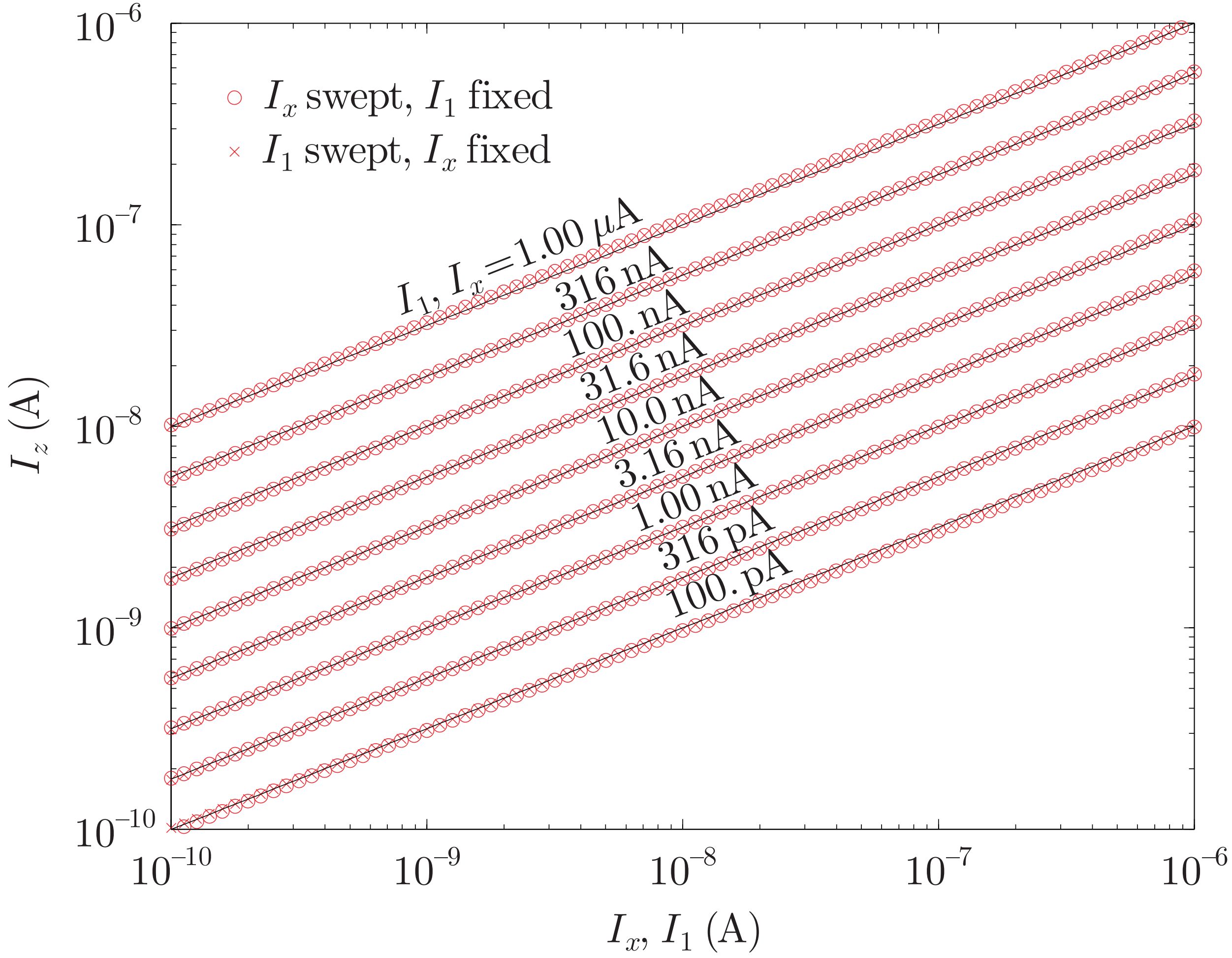
Experimental Measurements: Square-Root Circuit



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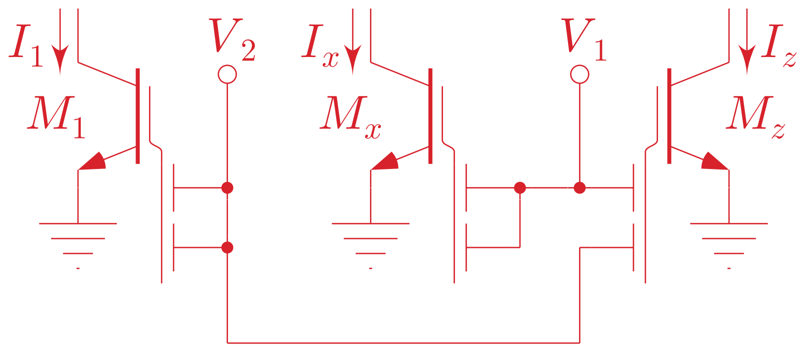

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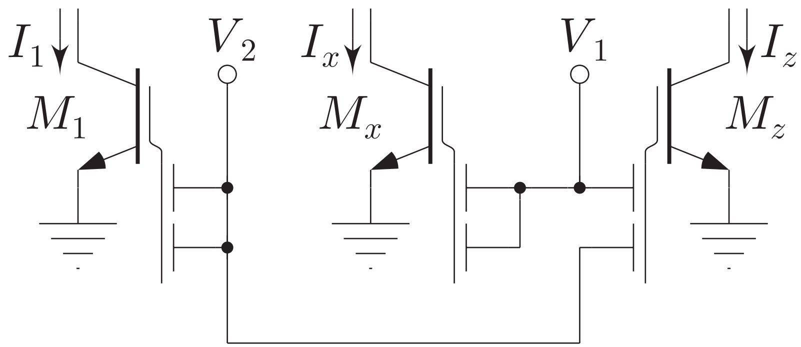

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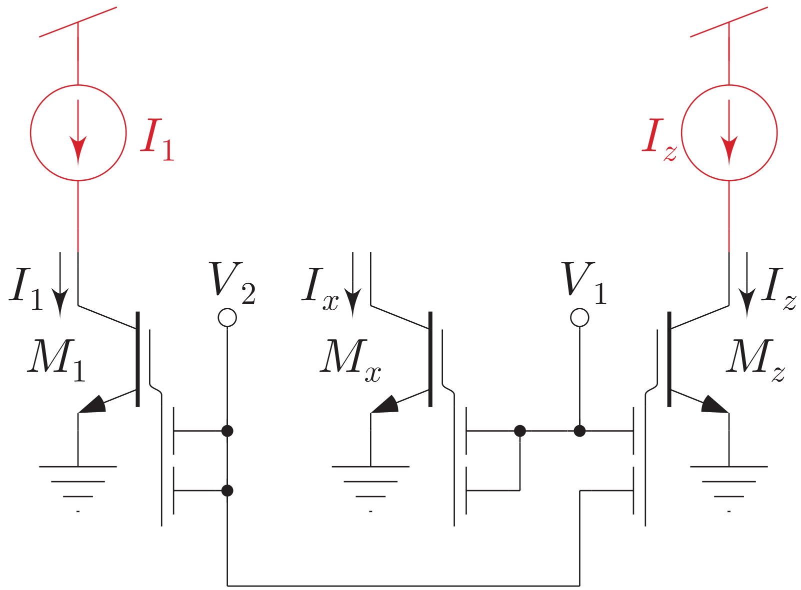

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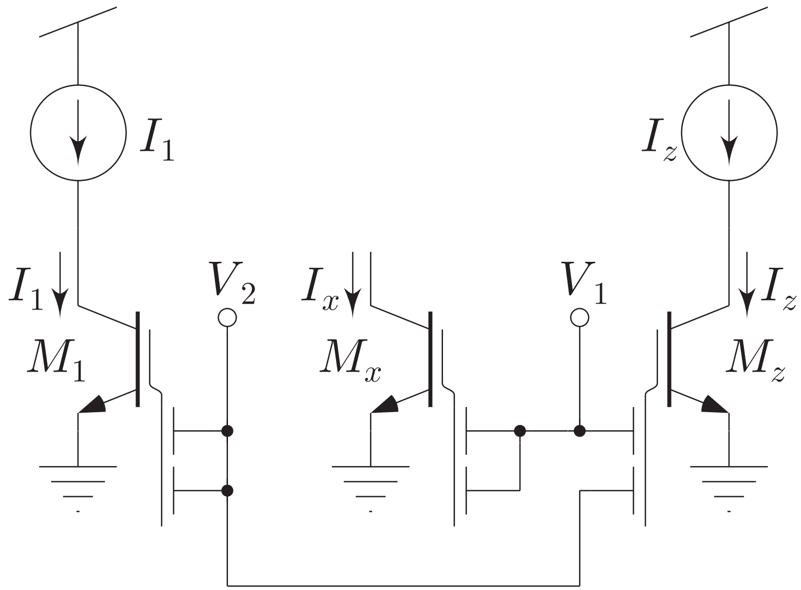

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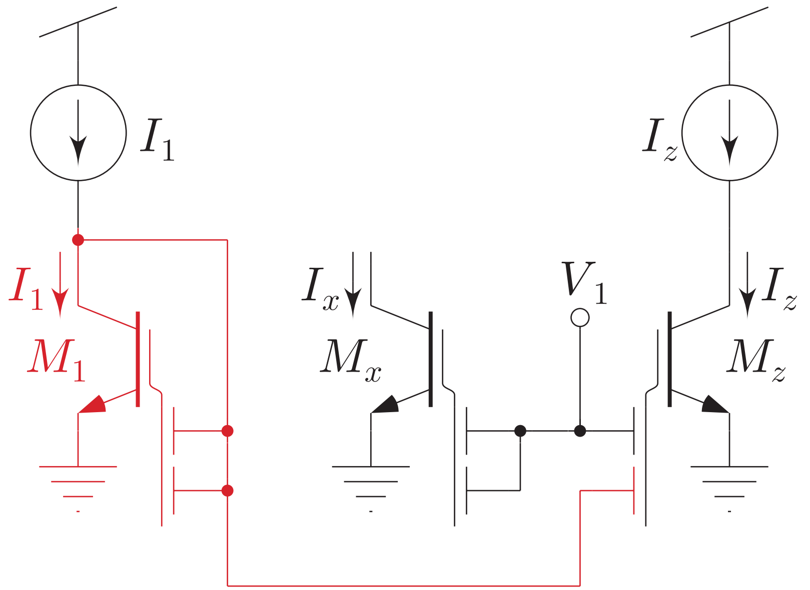

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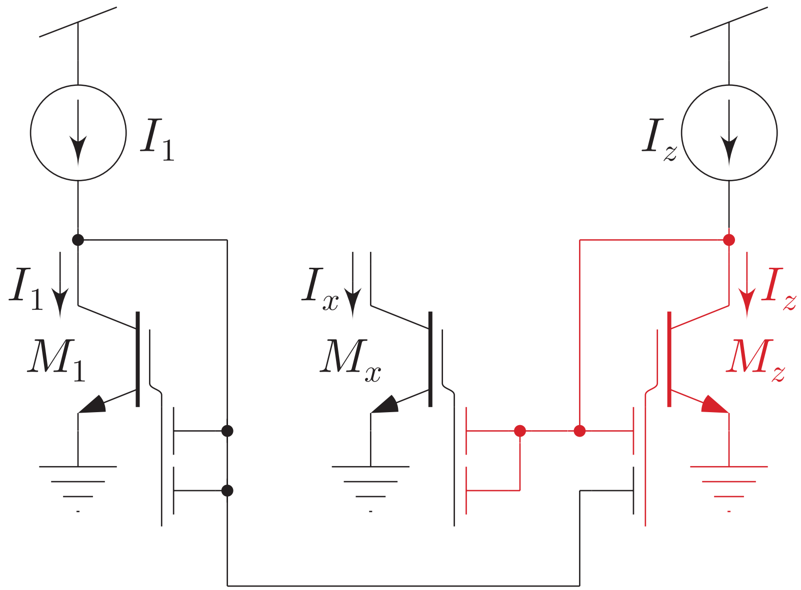

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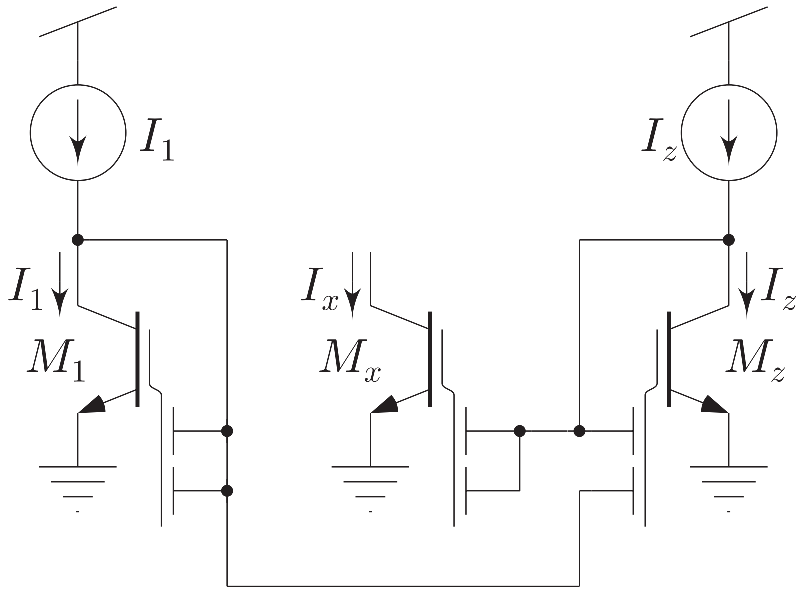

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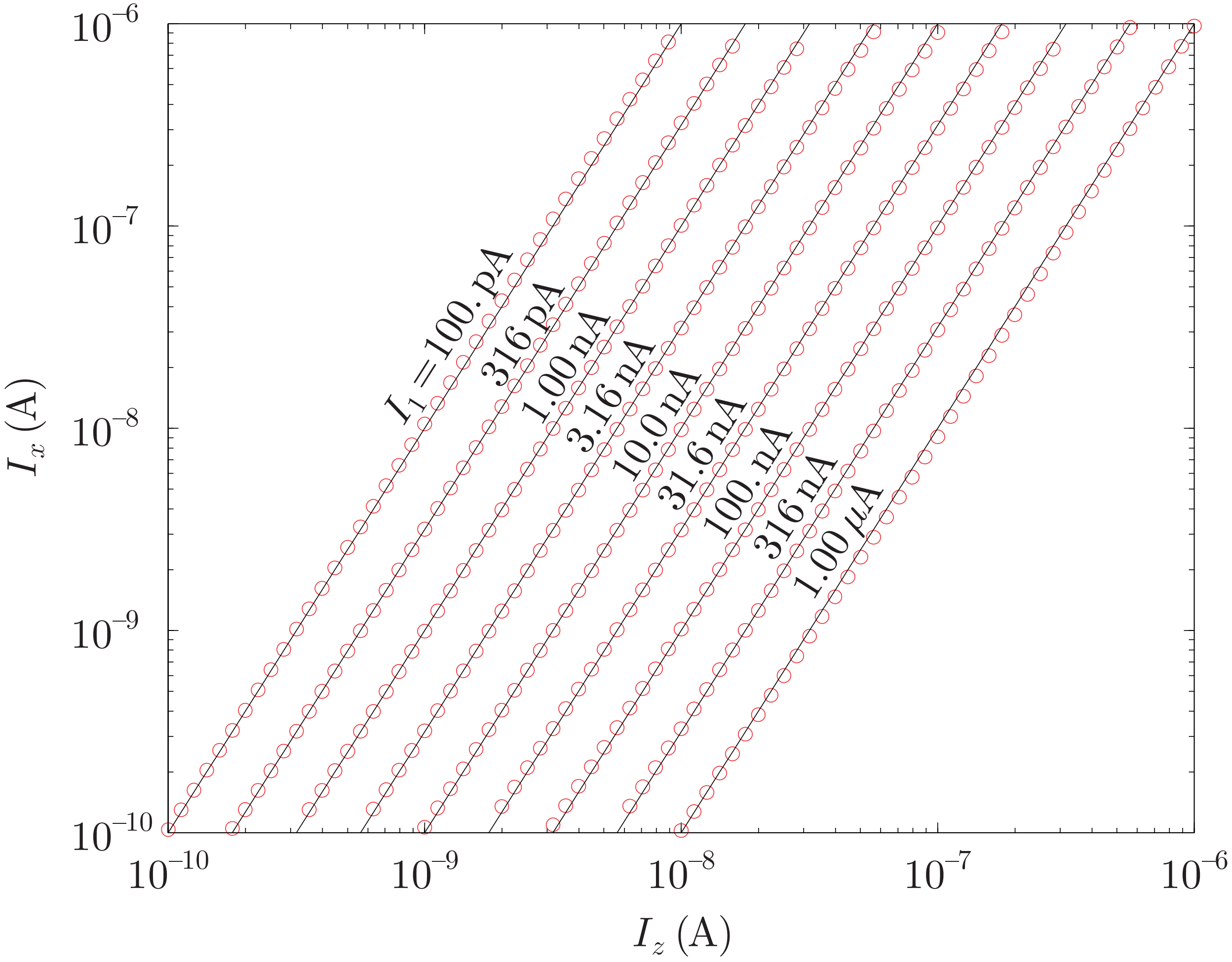

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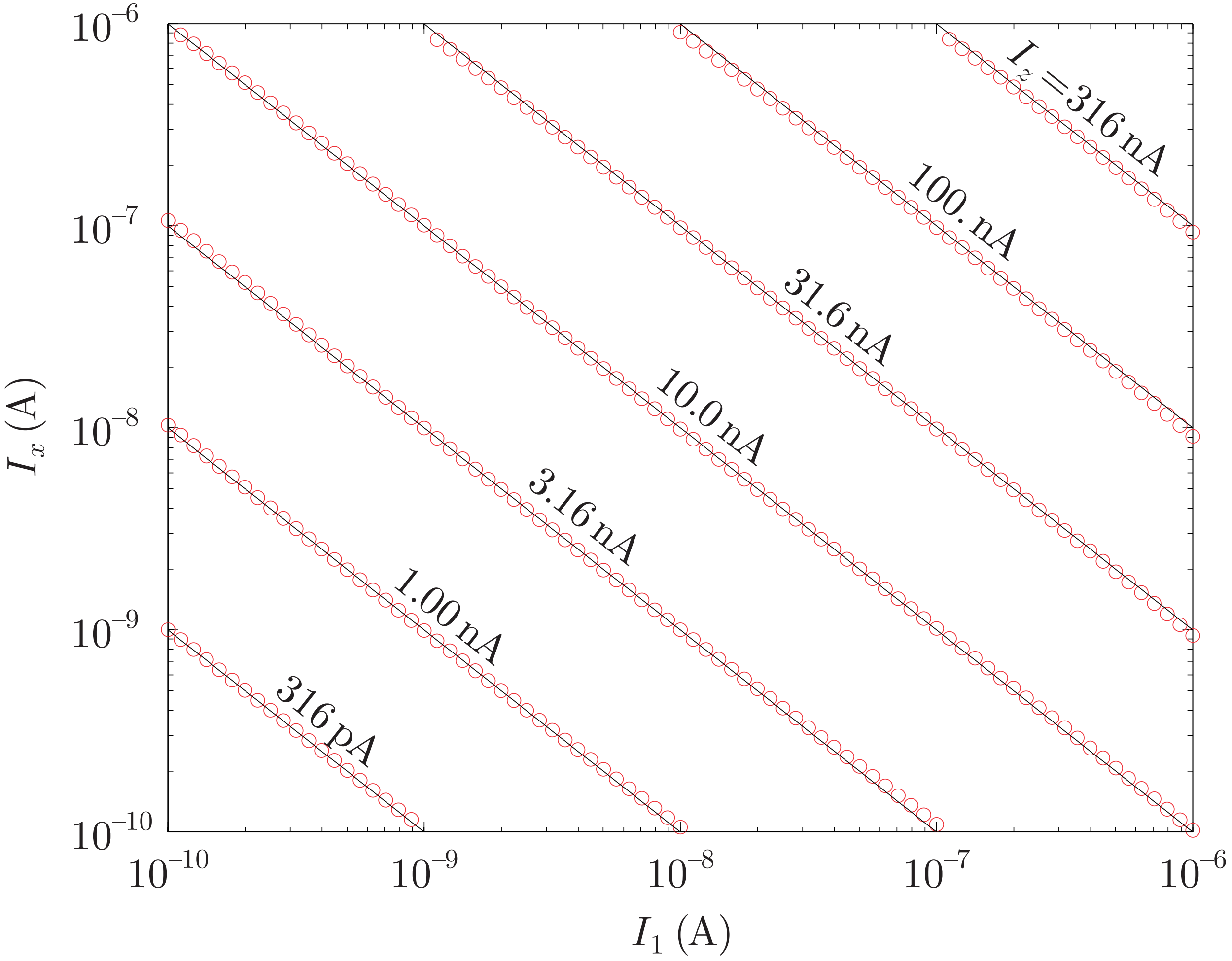
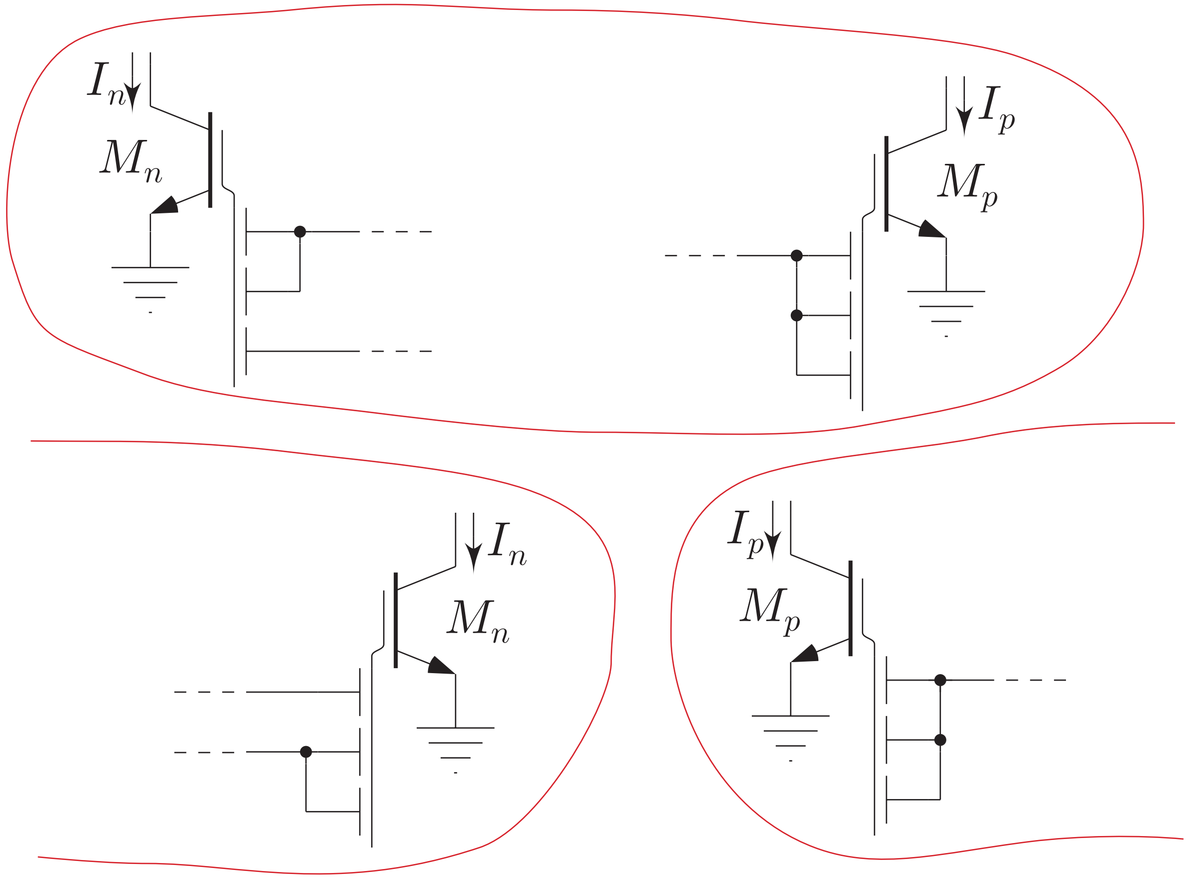


Static MITE Network Synthesis: Consolidation



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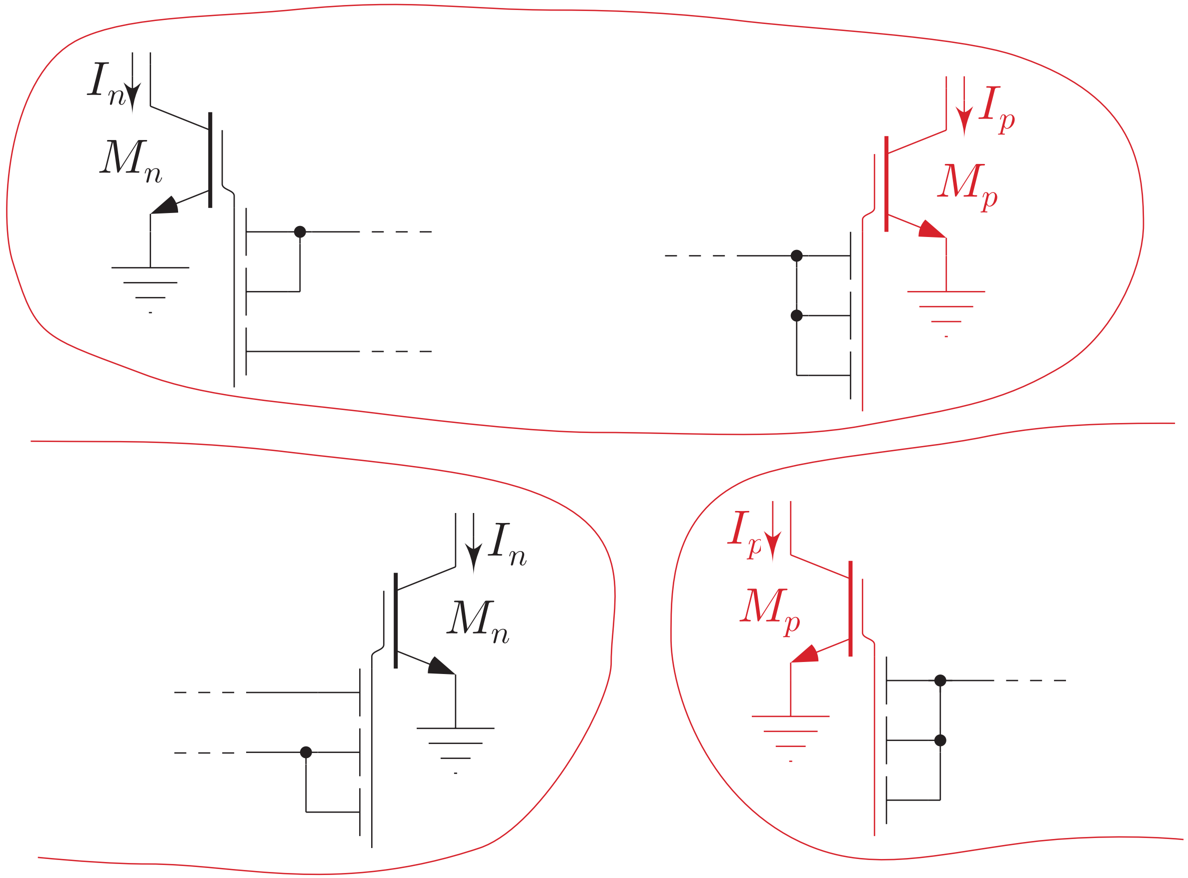

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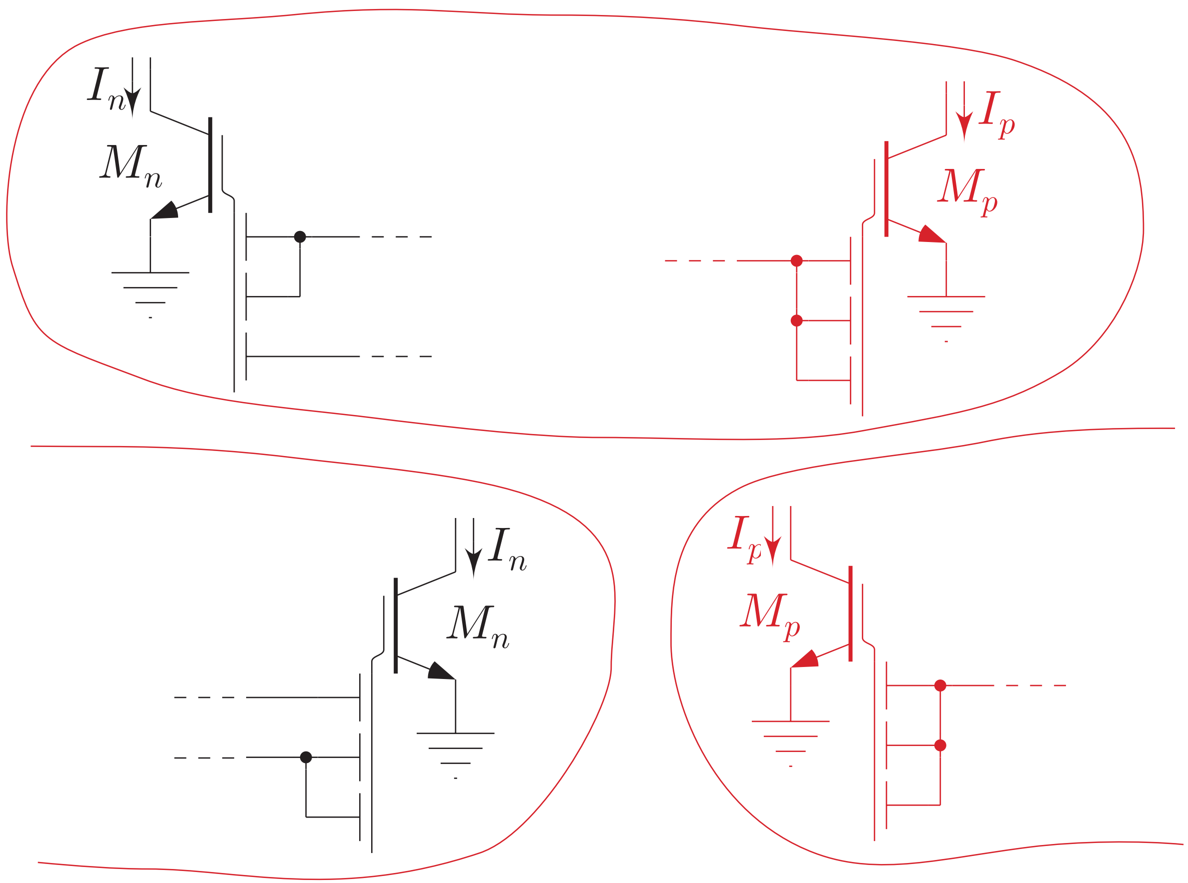

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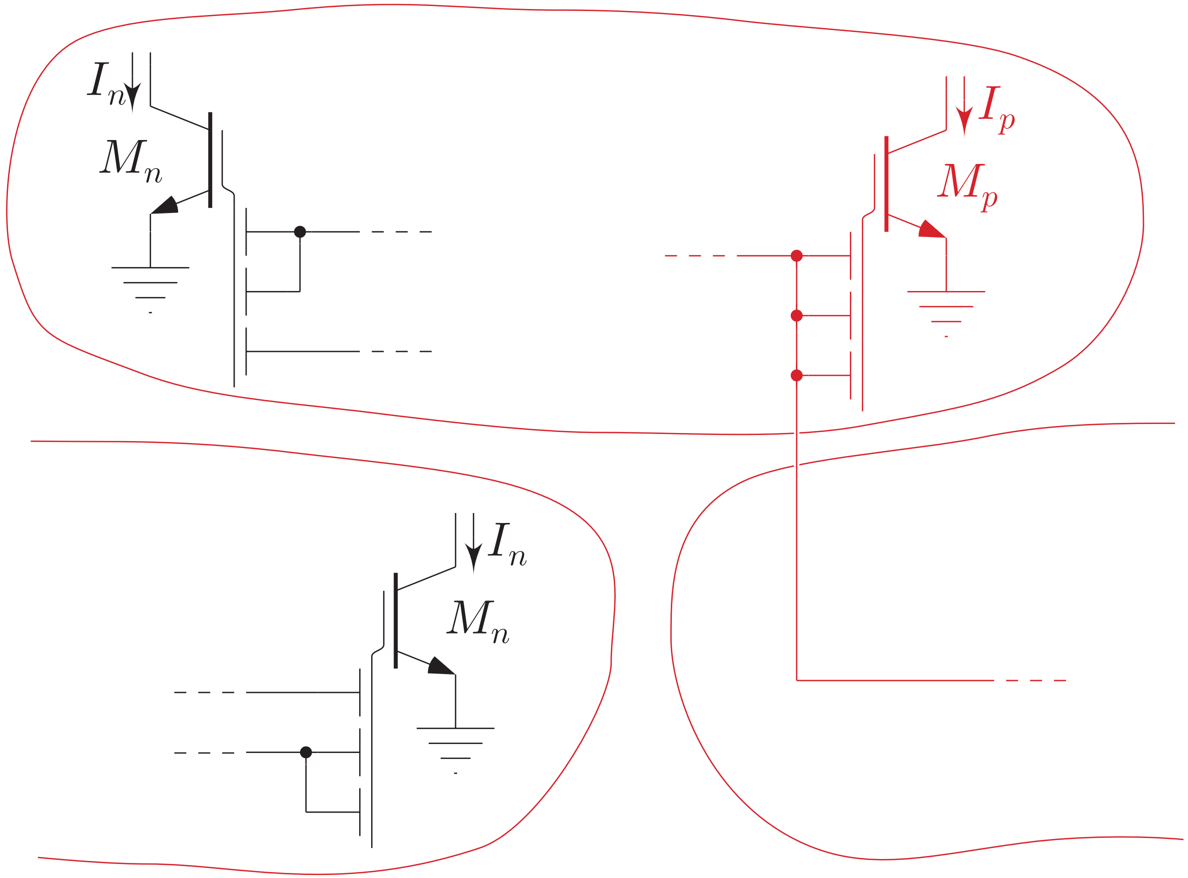

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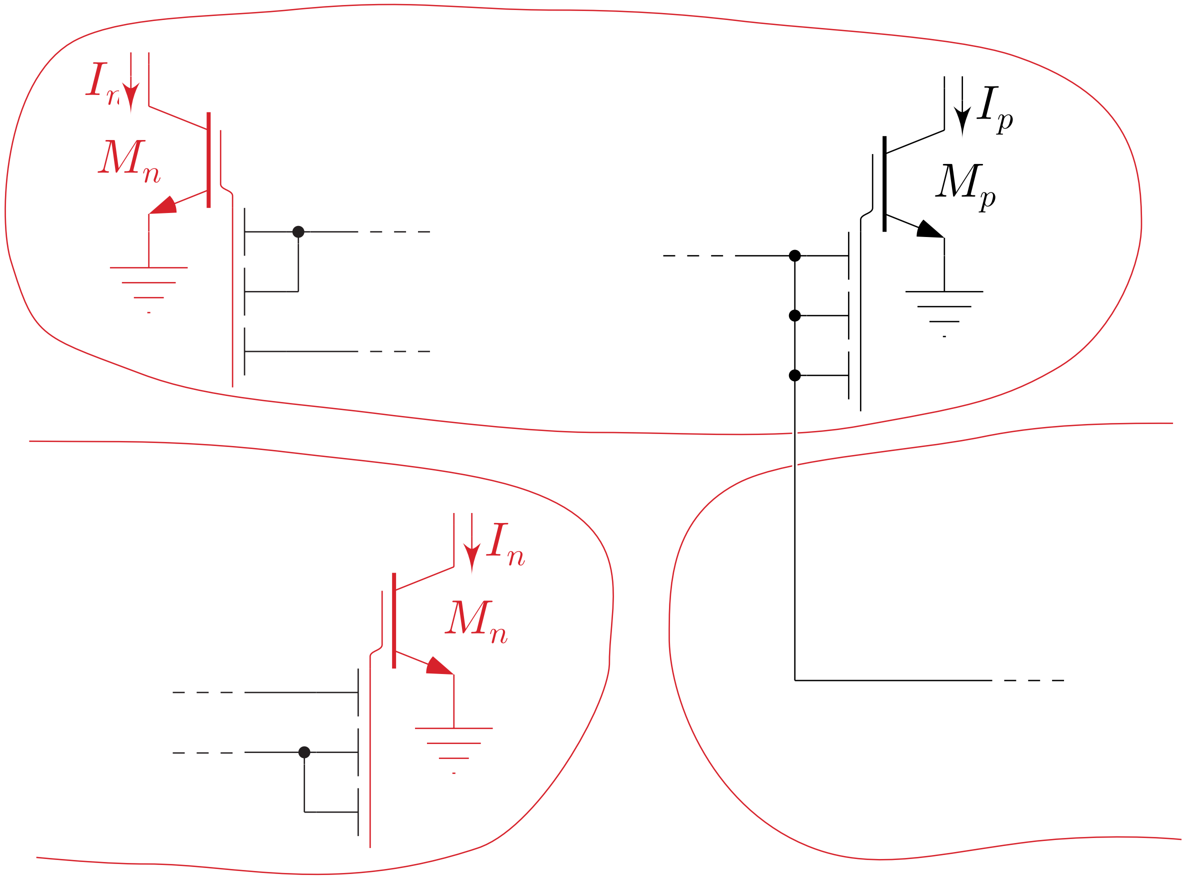

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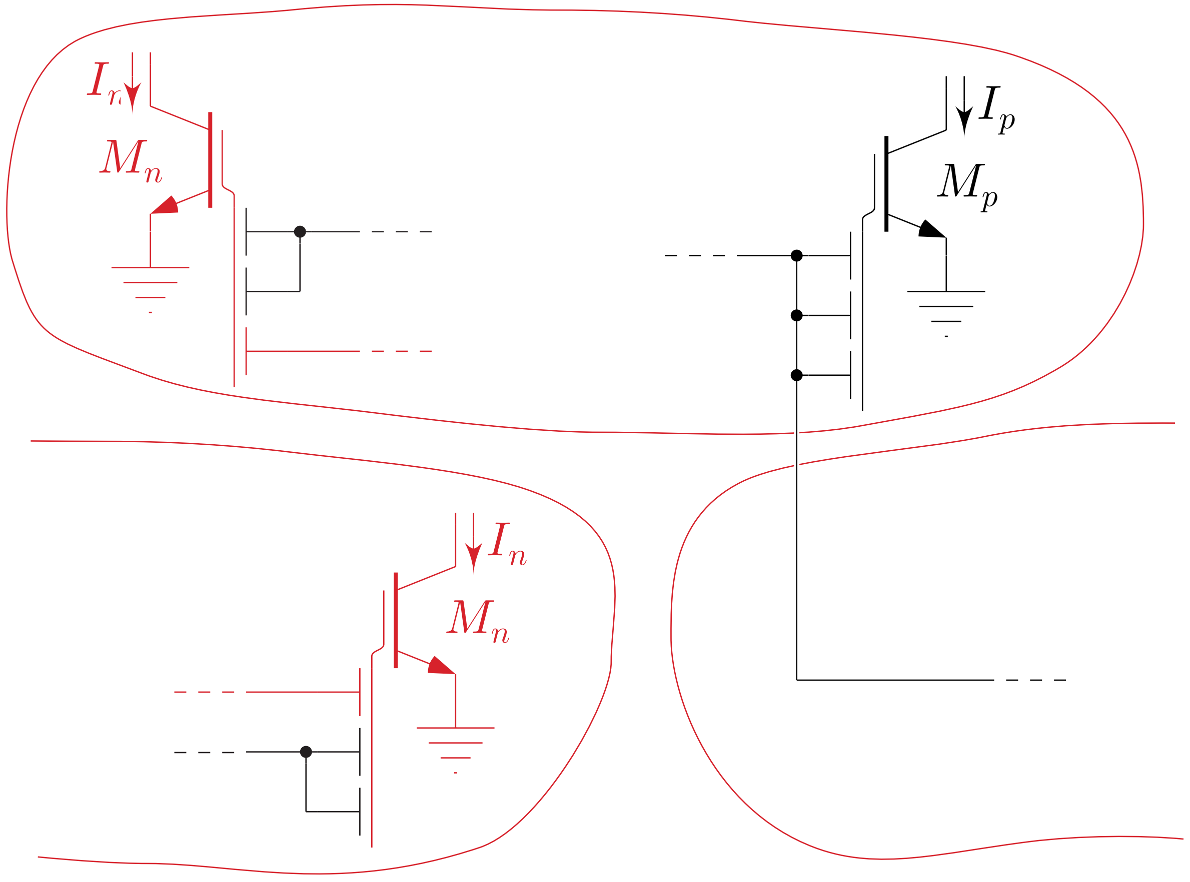

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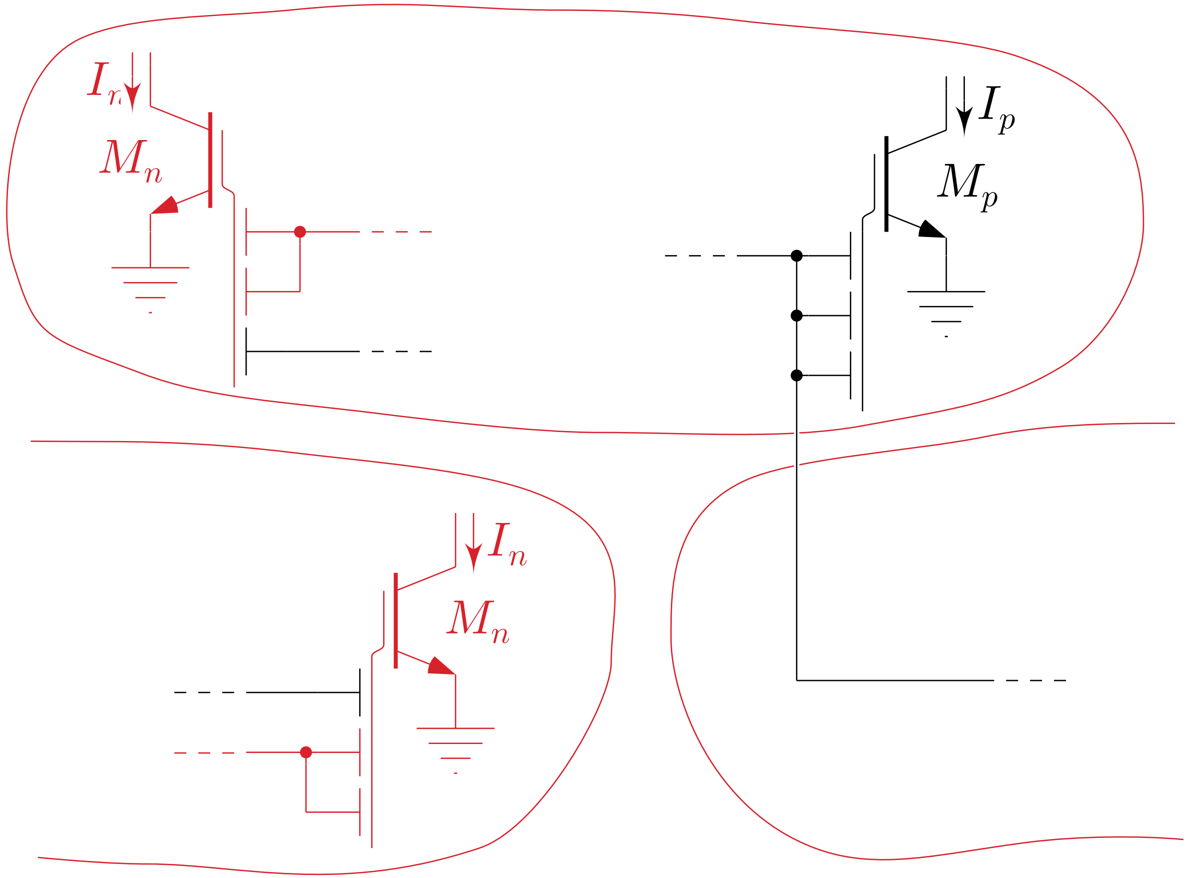

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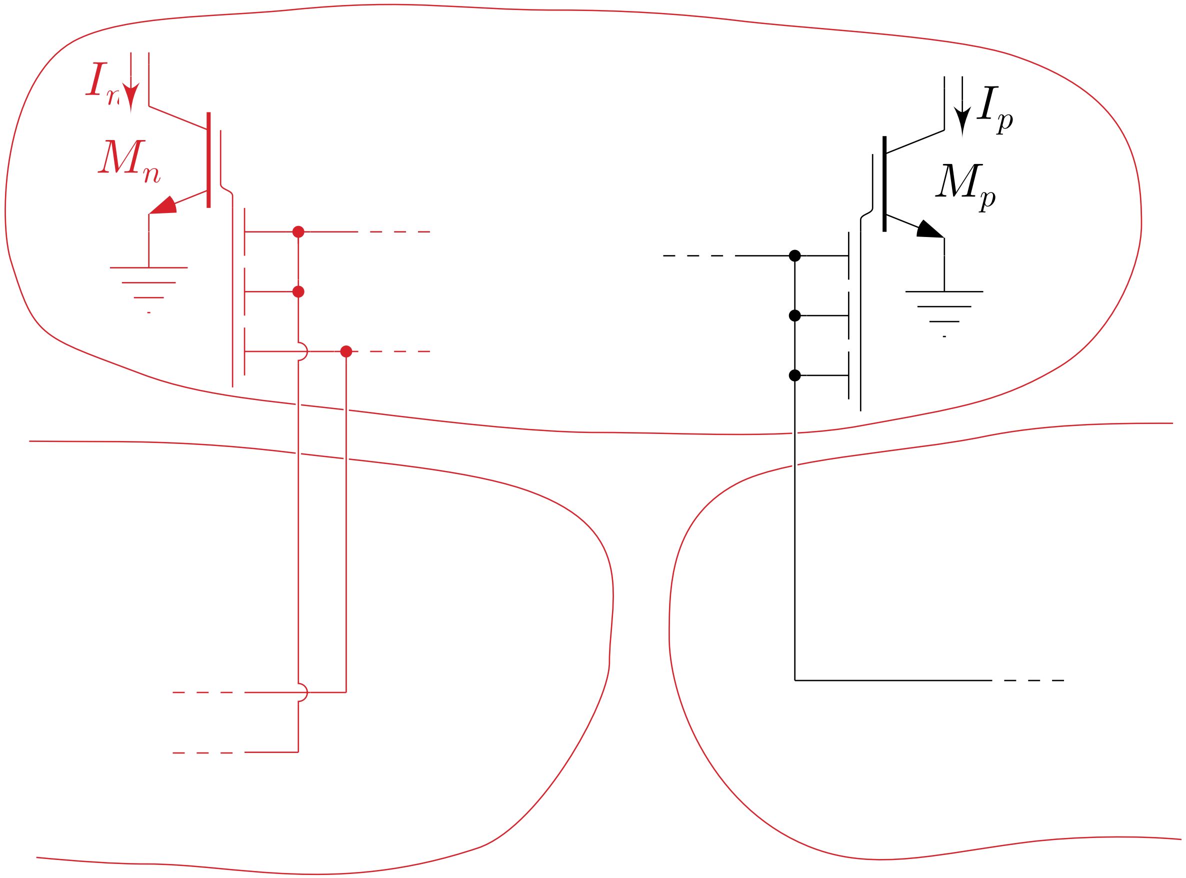

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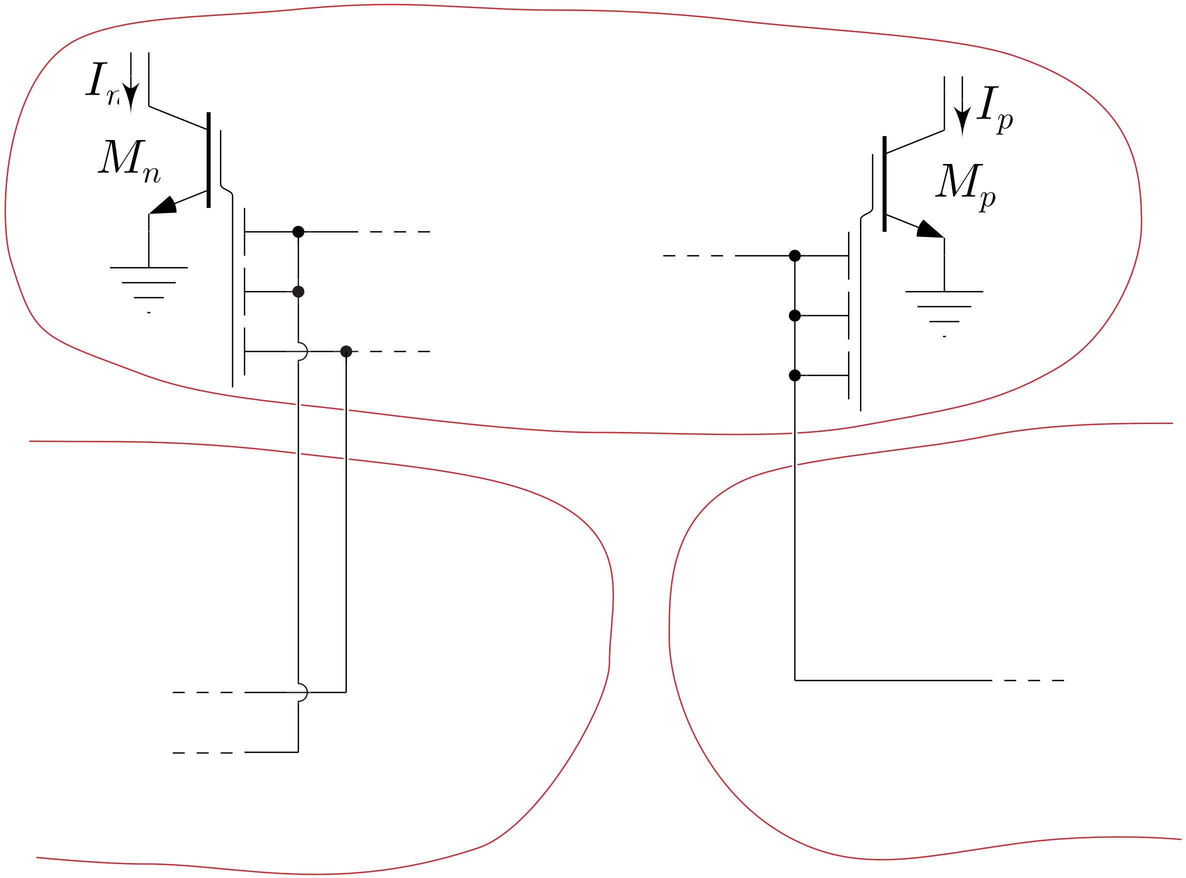

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Static MITE Network Synthesis: Vector Magnitude

Synthesize a two-dimensional vector-magnitude circuit implementing

$$r = \sqrt{x^2 + y^2}, \quad \text{where} \quad x > 0 \quad \text{and} \quad y > 0.$$

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$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \quad \Longrightarrow \quad I_r^2 = I_x^2 + I_y^2 \quad \Longrightarrow \quad I_r = \frac{I_x^2}{I_r} + \frac{I_y^2}{I_r}$$

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$$x \equiv \frac{I_x}{I_1}, \quad y \equiv \frac{I_y}{I_1}, \quad \text{and} \quad r \equiv \frac{I_r}{I_1}.$$

We substitute these into the original equation and rearrange to obtain

$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \quad \Longrightarrow \quad I_r^2 = I_x^2 + I_y^2 \quad \Longrightarrow \quad I_r = \underbrace{\frac{I_x^2}{I_r}}_{I_{r1}} + \underbrace{\frac{I_y^2}{I_r}}_{I_{r2}}$$

Static MITE Network Synthesis: Vector Magnitude

TLP: $I_{r1} I_r = I_x^2$

$I_{r2} I_r = I_y^2$

KCL: $I_r = I_{r1} + I_{r2}$

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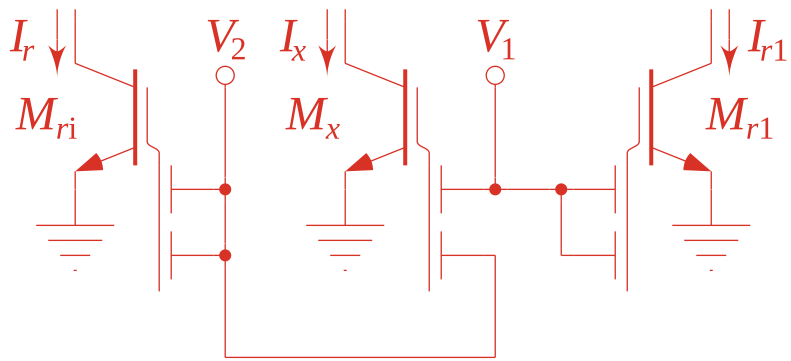

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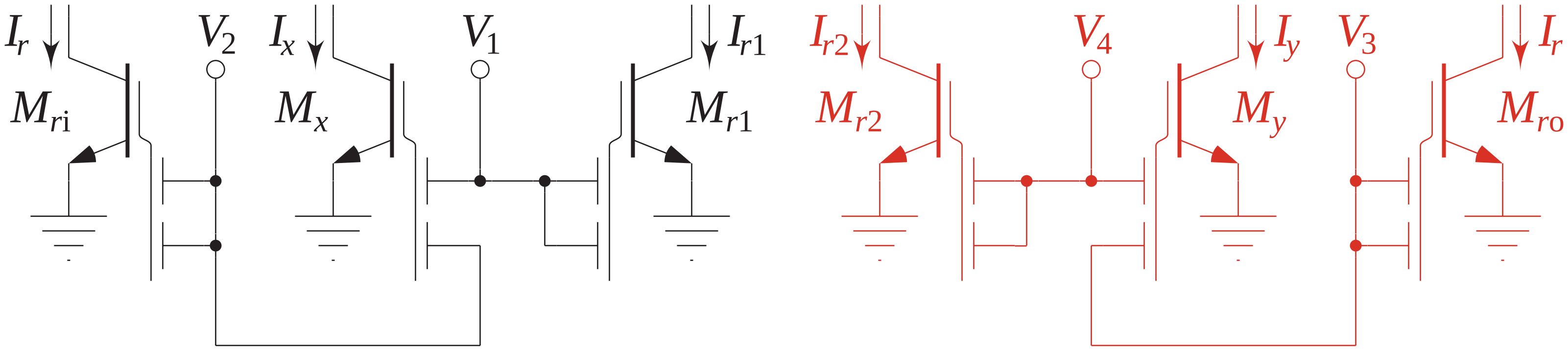

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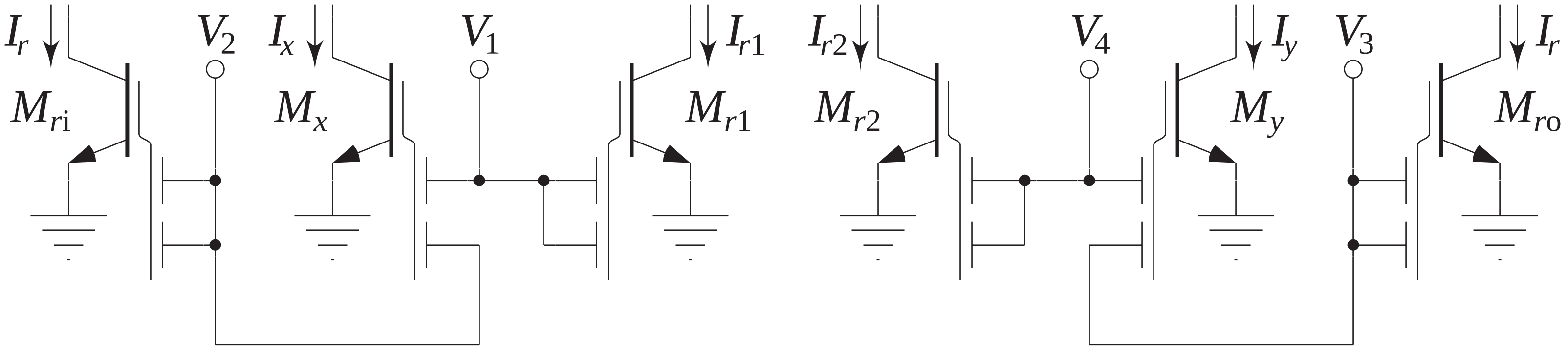

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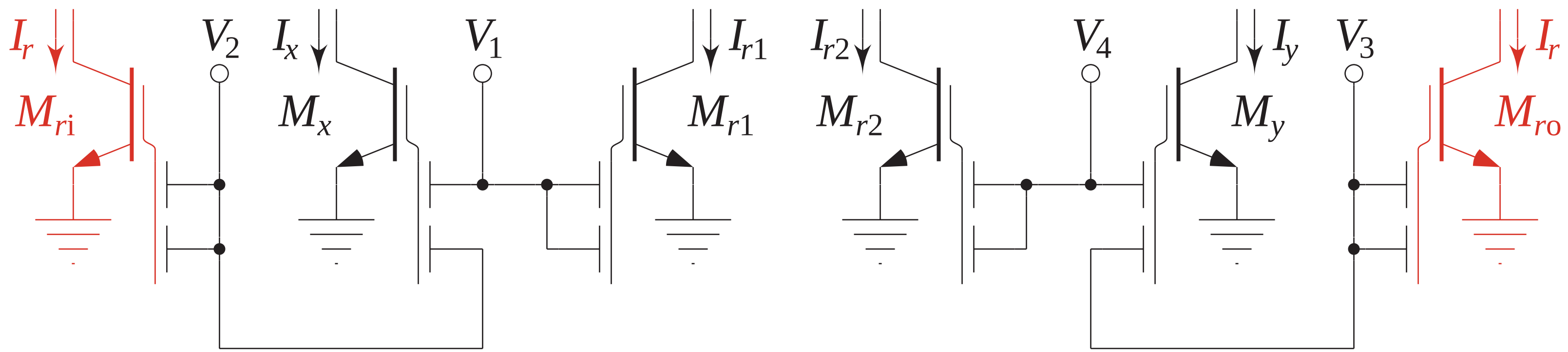

Static MITE Network Synthesis: Vector Magnitude

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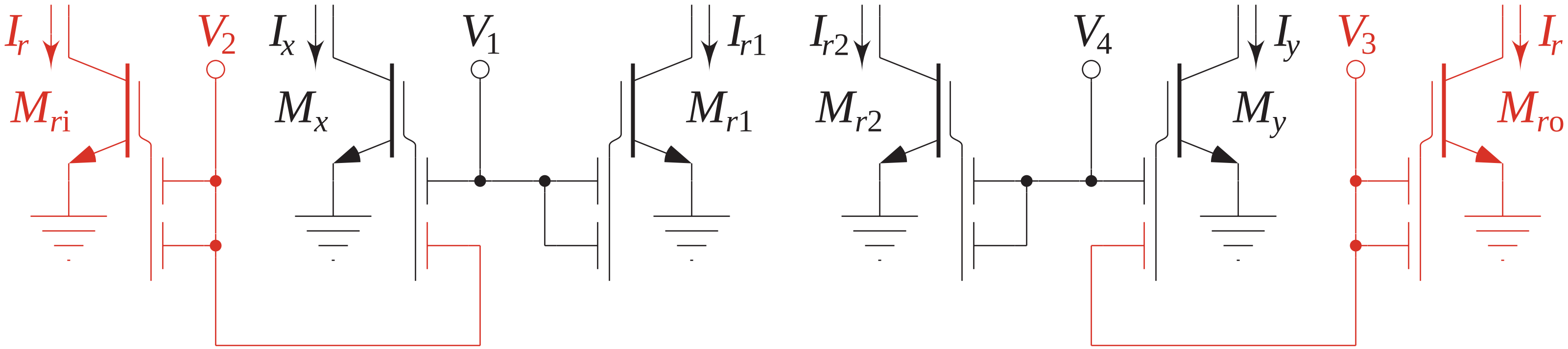

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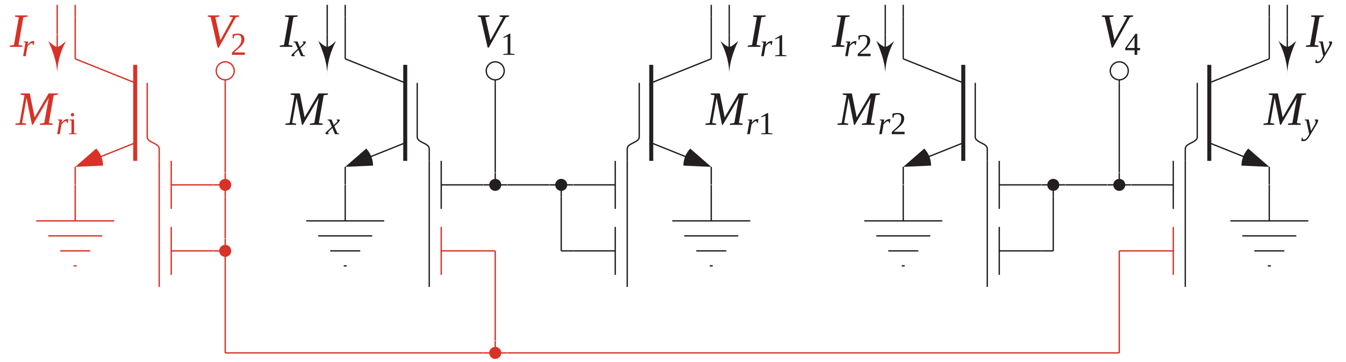

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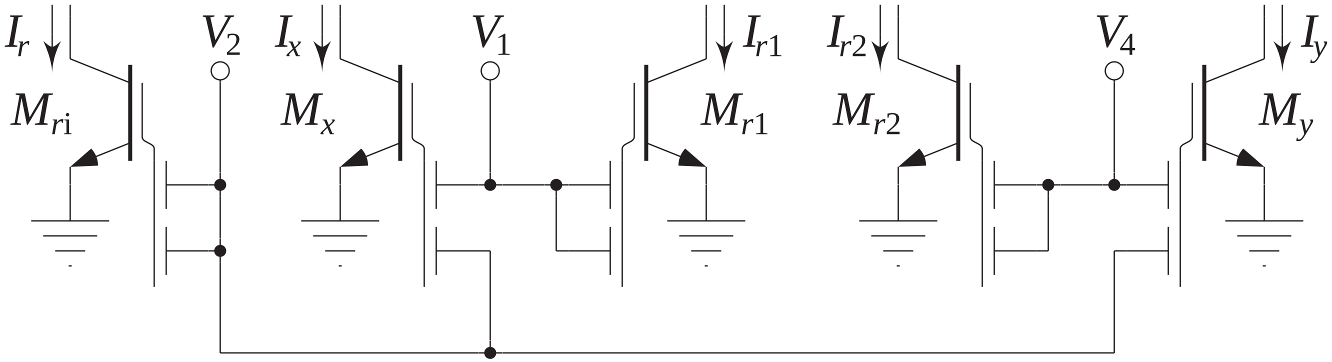

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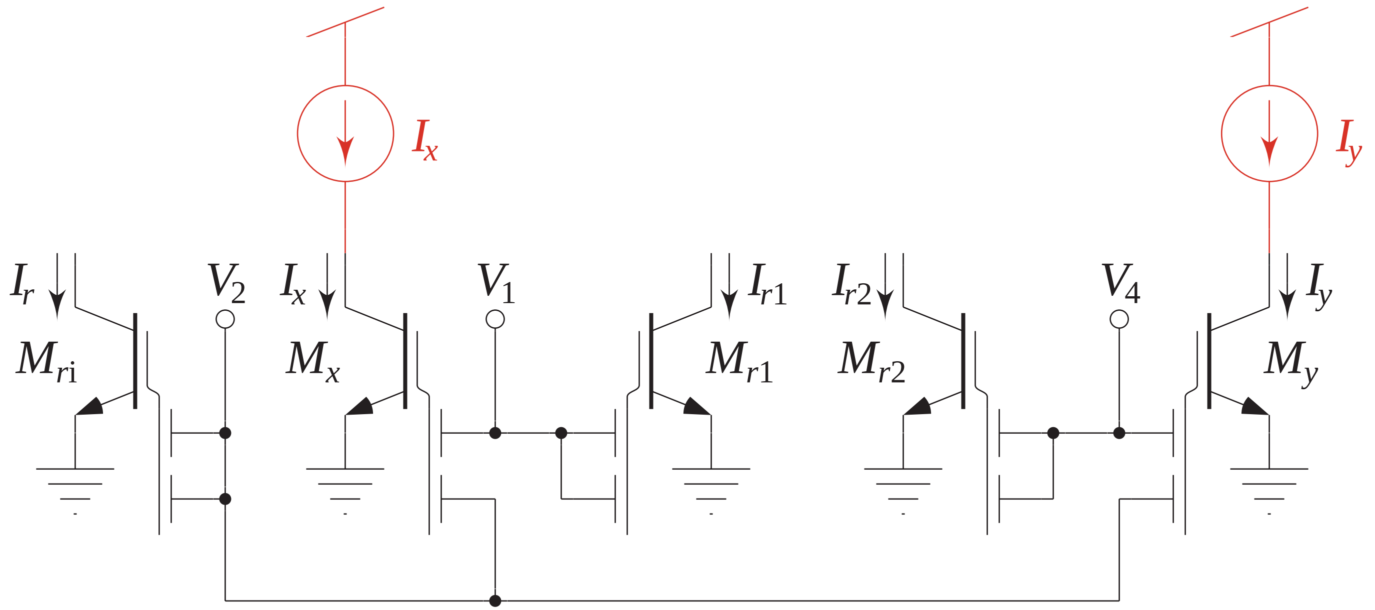

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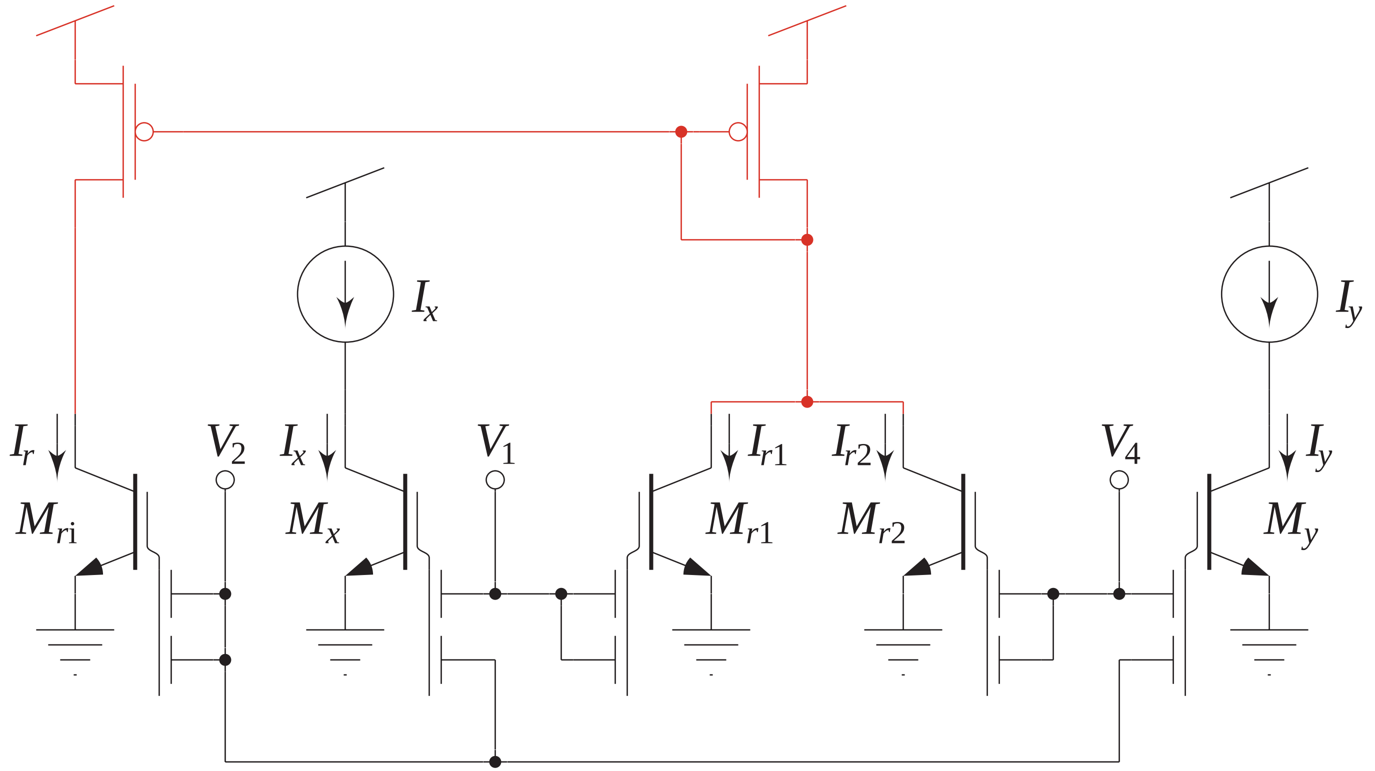

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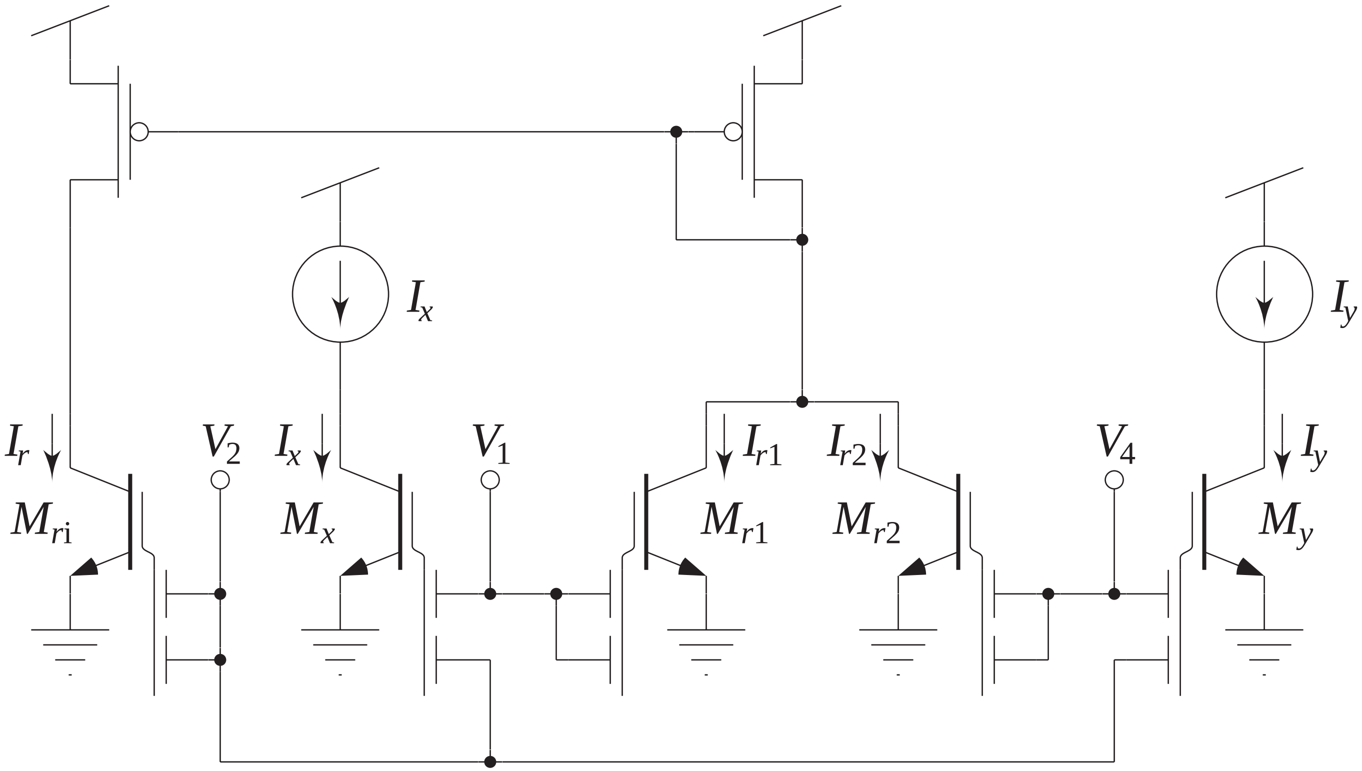

Static MITE Network Synthesis: Vector Magnitude

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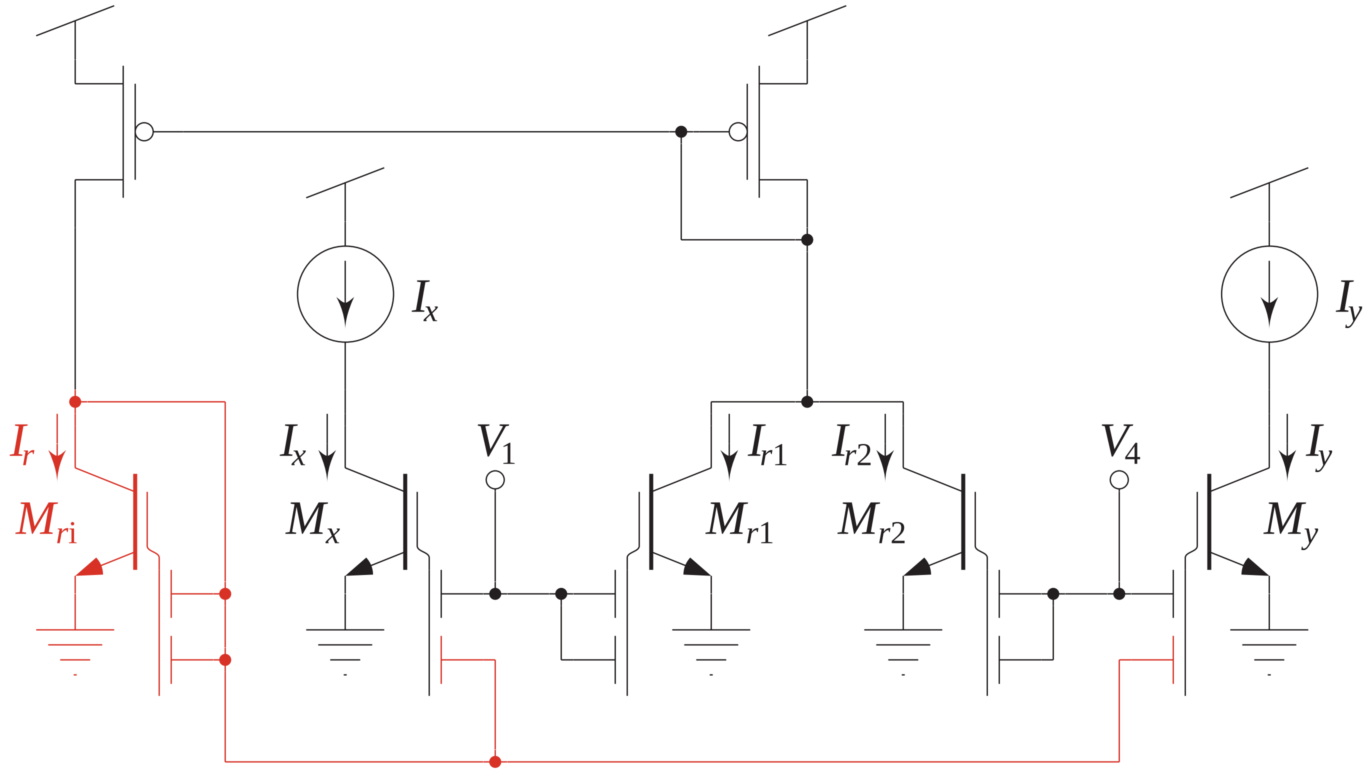

Static MITE Network Synthesis: Vector Magnitude

TLP: $I_{r1} I_r = I_x^2$, $I_{r2} I_r = I_y^2$

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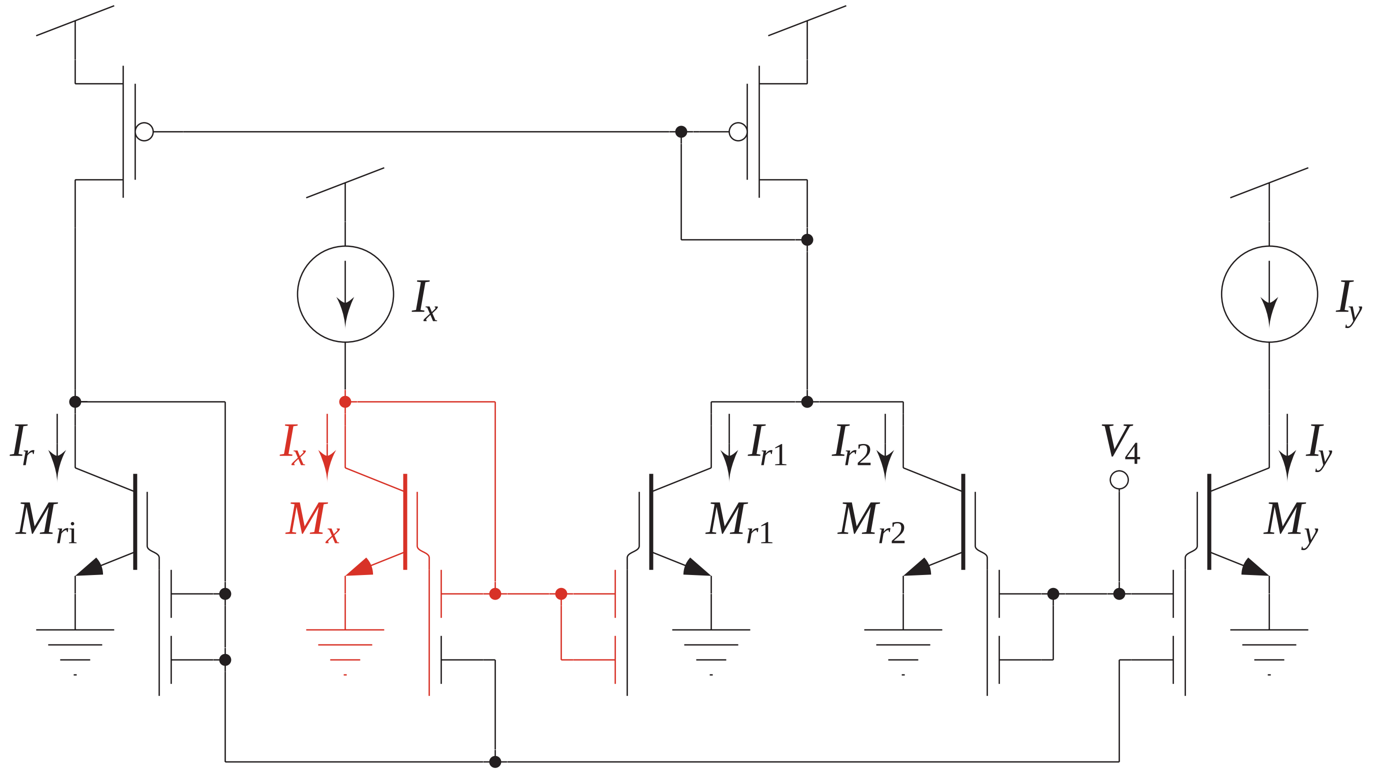

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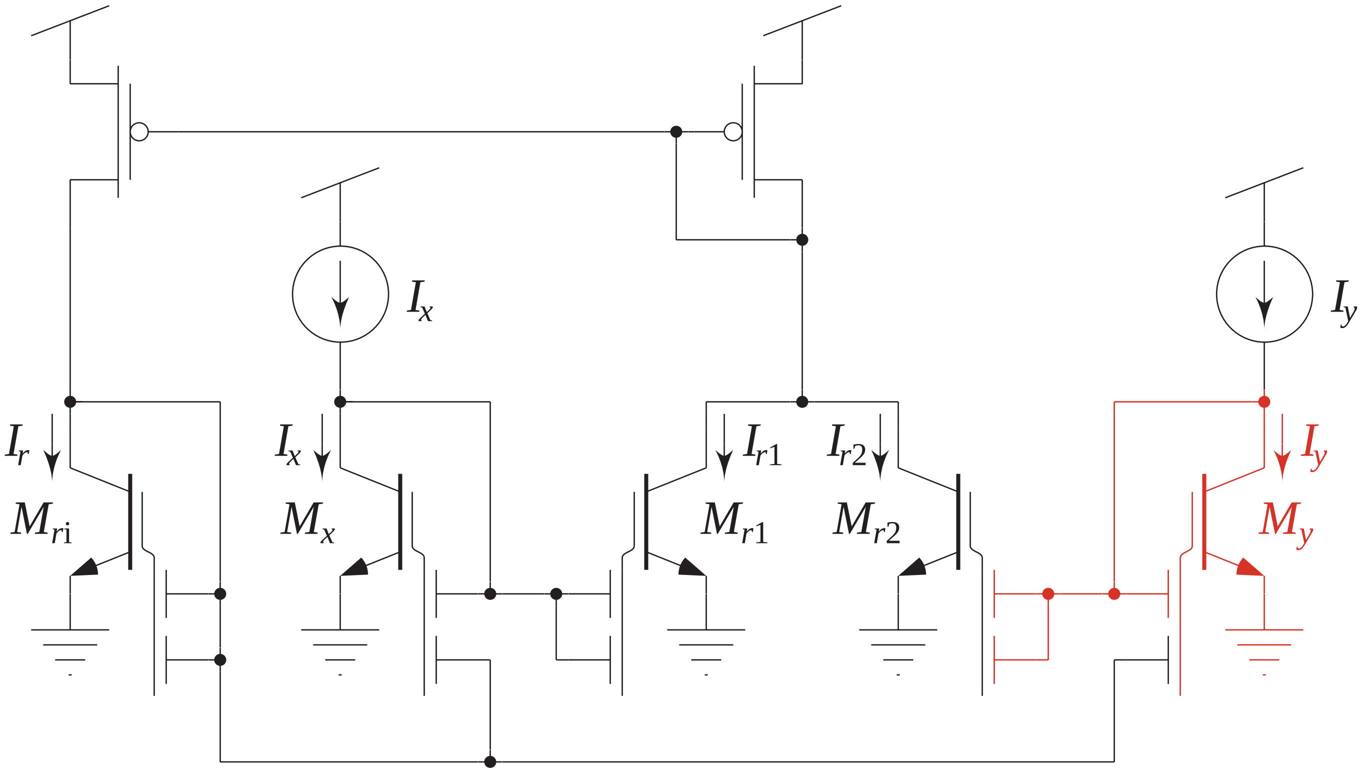

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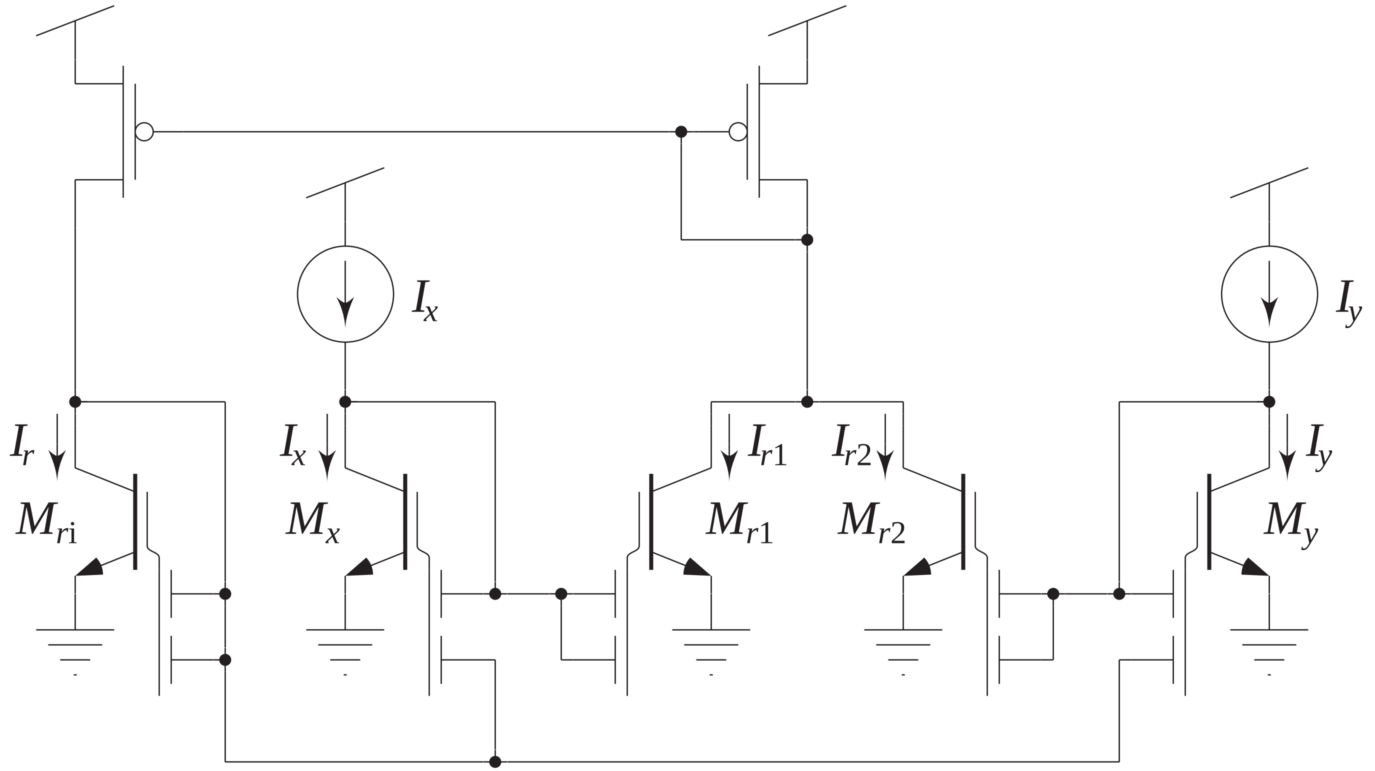

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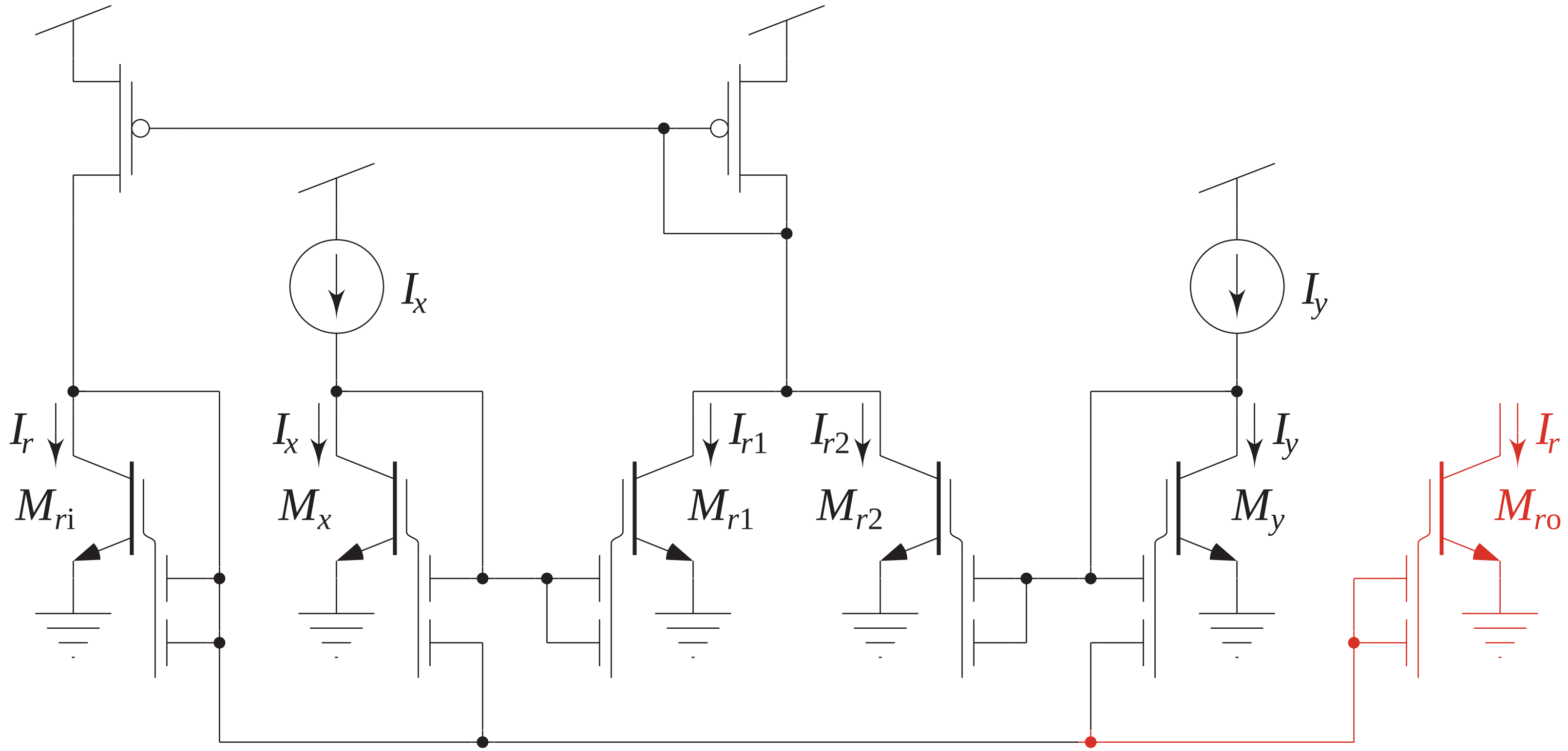

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Static MITE Network Synthesis: Vector Magnitude

TLP: $I_{r1} I_r = I_x^2$

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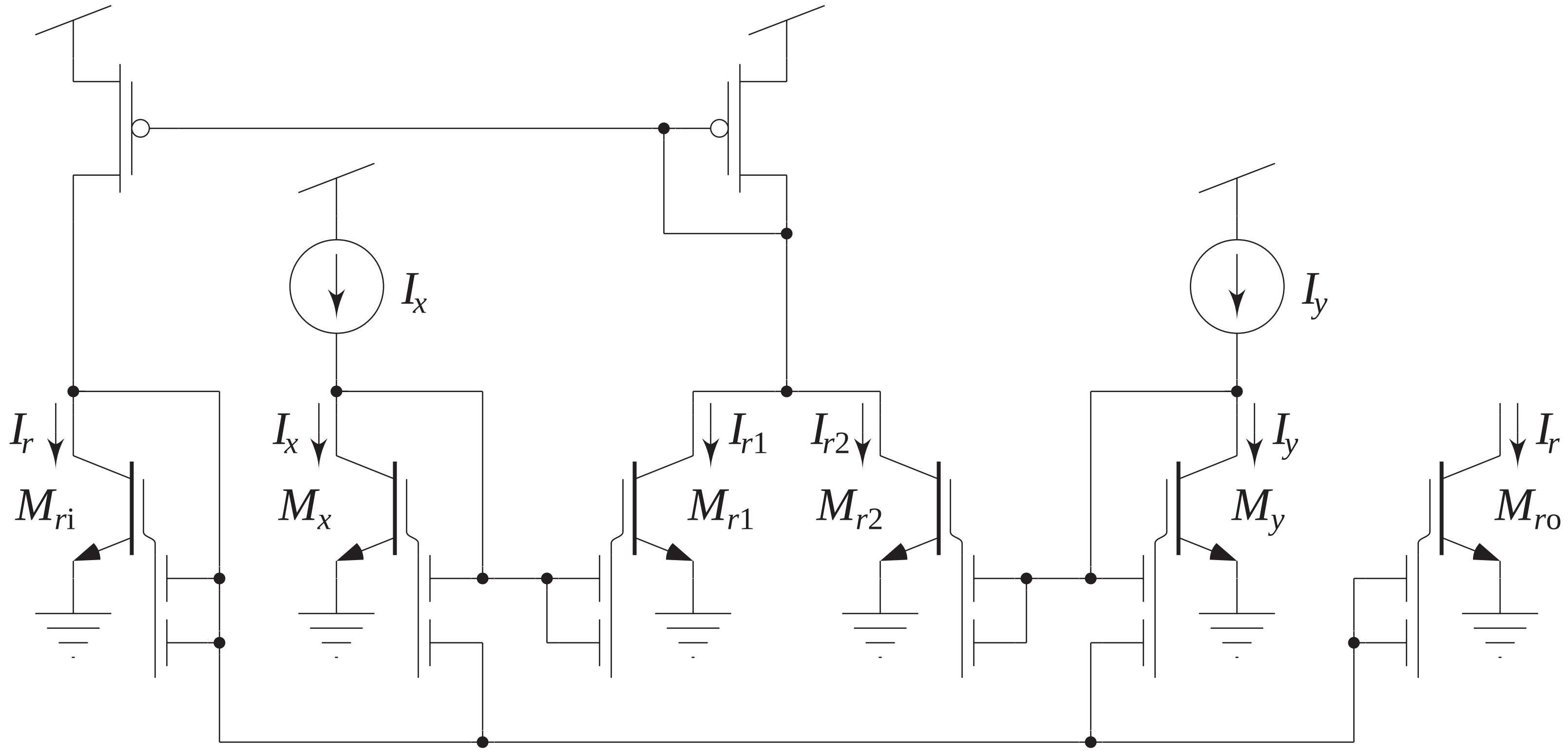

Static MITE Network Synthesis: Vector Normalizer

Synthesize a two-dimensional vector-normalization circuit implementing

$$u = \frac{x}{\sqrt{x^2 + y^2}} \quad \text{and} \quad v = \frac{y}{\sqrt{x^2 + y^2}}, \quad \text{where} \quad x > 0 \quad \text{and} \quad y > 0.$$

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Each equation shares $r \equiv \sqrt{x^2 + y^2}$, which we can use to decompose the system as

$$u = \frac{x}{r}, \quad v = \frac{y}{r}, \quad \text{and} \quad r = \sqrt{x^2 + y^2}, \quad \text{where} \quad x > 0 \quad \text{and} \quad y > 0.$$

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Static MITE Network Synthesis: Vector Normalizer

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We represent each signal as a ratio of a signal current to the unit current:

$$x \equiv \frac{I_x}{I_1}, \quad y \equiv \frac{I_y}{I_1}, \quad u \equiv \frac{I_u}{I_1}, \quad v \equiv \frac{I_v}{I_1}, \quad \text{and} \quad r \equiv \frac{I_r}{I_1}.$$

Static MITE Network Synthesis: Vector Normalizer

We substitute these into the original equations and rearrange to obtain

$$\frac{I_u}{I_1} = \frac{I_x/I_1}{I_r/I_1} \quad \text{and} \quad \frac{I_v}{I_1} = \frac{I_y/I_1}{I_r/I_1}$$

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and

$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2}$$

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Static MITE Network Synthesis: Vector Normalizer

We substitute these into the original equations and rearrange to obtain

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and

$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \quad \Longrightarrow \quad I_r^2 = I_x^2 + I_y^2$$

Static MITE Network Synthesis: Vector Normalizer

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and

$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \quad \Longrightarrow \quad I_r^2 = I_x^2 + I_y^2 \quad \Longrightarrow \quad I_r = \frac{I_x^2}{I_r} + \frac{I_y^2}{I_r}$$

Static MITE Network Synthesis: Vector Normalizer

We substitute these into the original equations and rearrange to obtain

$$\frac{I_u}{I_1} = \frac{I_x/I_1}{I_r/I_1} \quad \text{and} \quad \frac{I_v}{I_1} = \frac{I_y/I_1}{I_r/I_1} \quad \Longrightarrow \quad I_u I_r = I_x I_1 \quad \text{and} \quad I_v I_r = I_y I_1$$

and

$$\frac{I_r}{I_1} = \sqrt{\left(\frac{I_x}{I_1}\right)^2 + \left(\frac{I_y}{I_1}\right)^2} \quad \Longrightarrow \quad I_r^2 = I_x^2 + I_y^2 \quad \Longrightarrow \quad I_r = \underbrace{\frac{I_x^2}{I_r}}_{I_{r1}} + \underbrace{\frac{I_y^2}{I_r}}_{I_{r2}}$$

Static MITE Network Synthesis: Vector Normalizer

TLP: $I_{r1}I_r = I_x^2$ $\quad I_u I_r = I_x I_1$ $\quad$ KCL: $I_r = I_{r1} + I_{r2}$

$I_{r2}I_r = I_y^2$ $\quad I_v I_r = I_y I_1$

Static MITE Network Synthesis: Vector Normalizer

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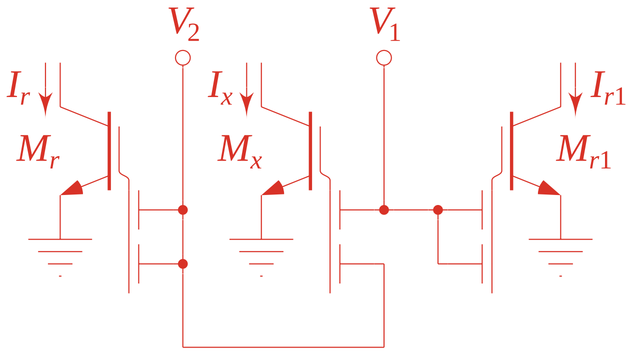

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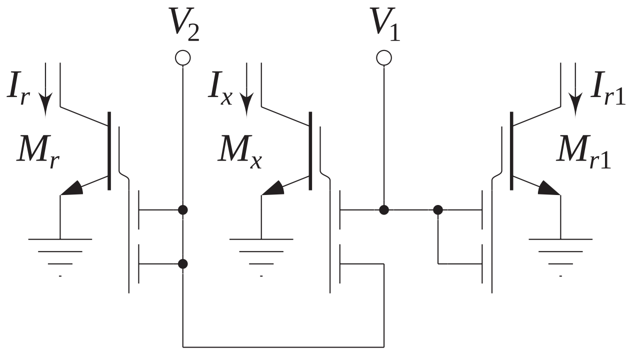

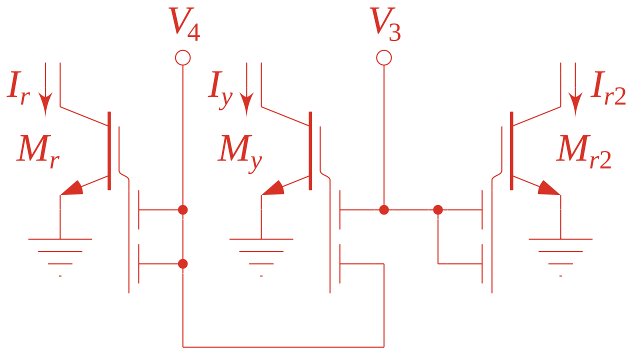

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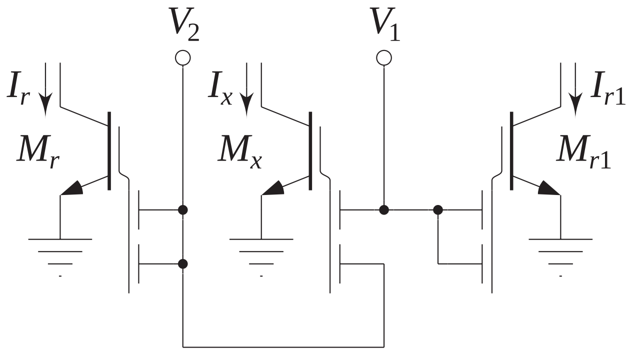

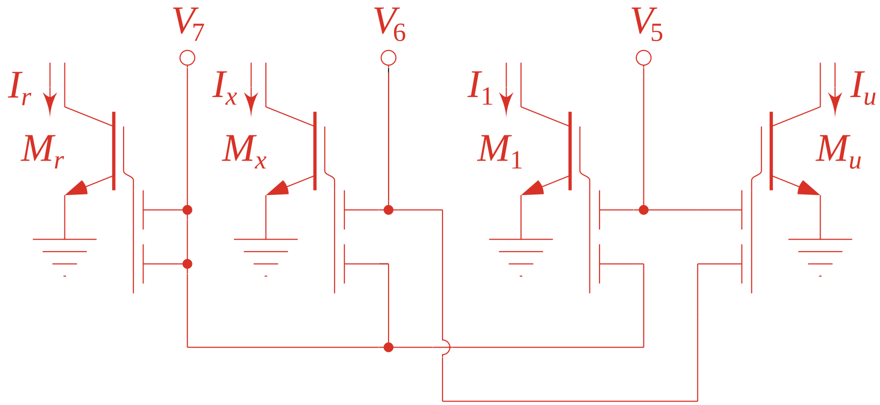

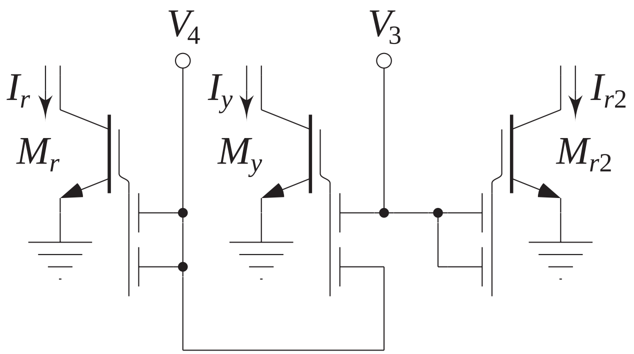

Static MITE Network Synthesis: Vector Normalizer

TLP: $I_{r1} I_r = I_x^2$ $\quad$ $I_u I_r = I_x I_1$ $\quad$ KCL: $I_r = I_{r1} + I_{r2}$

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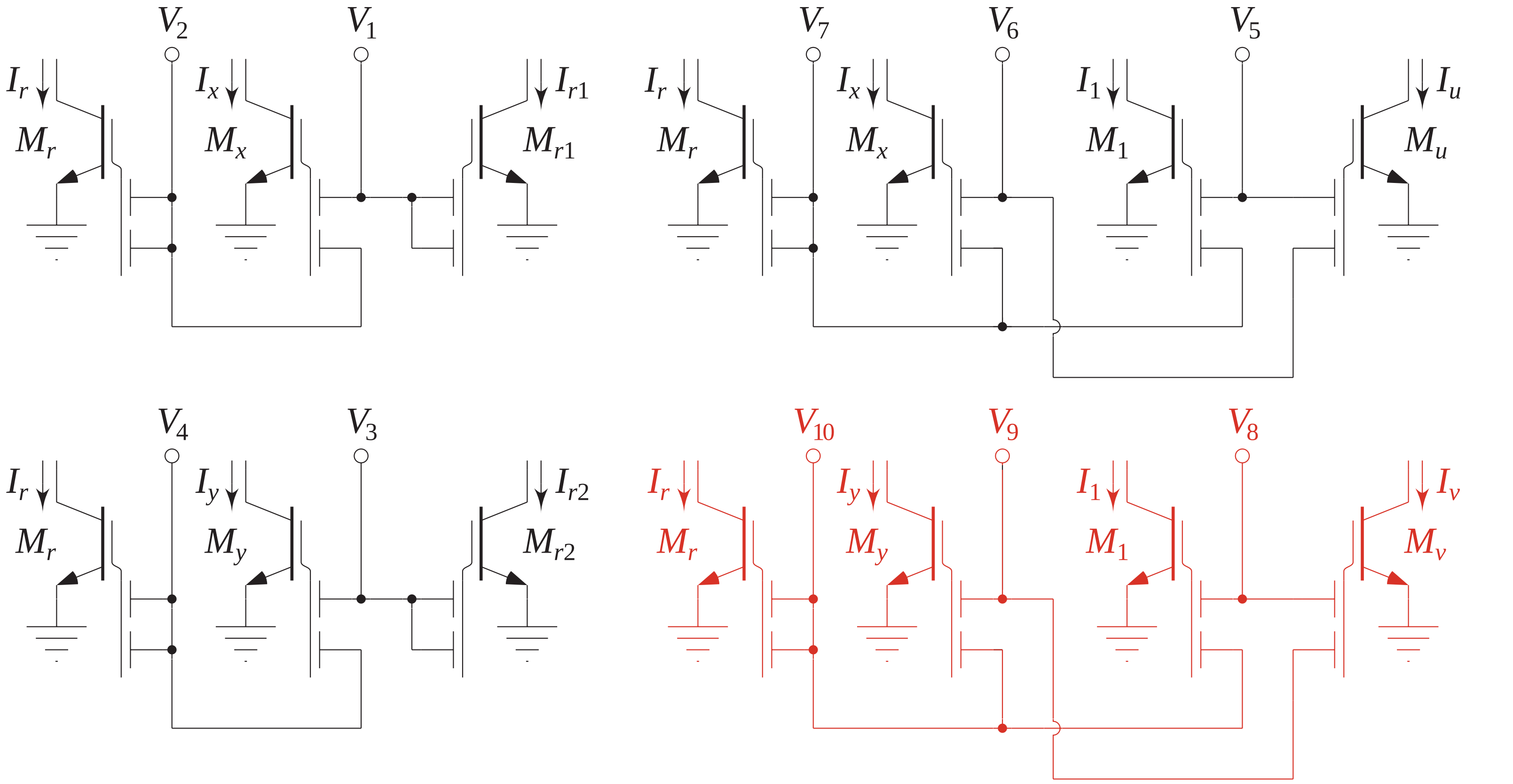

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Static MITE Network Synthesis: Vector Normalizer

TLP: $I_{r1}I_r = I_x^2$ $\quad I_uI_r = I_xI_1$ $\quad$ KCL: $I_r = I_{r1}+I_{r2}$

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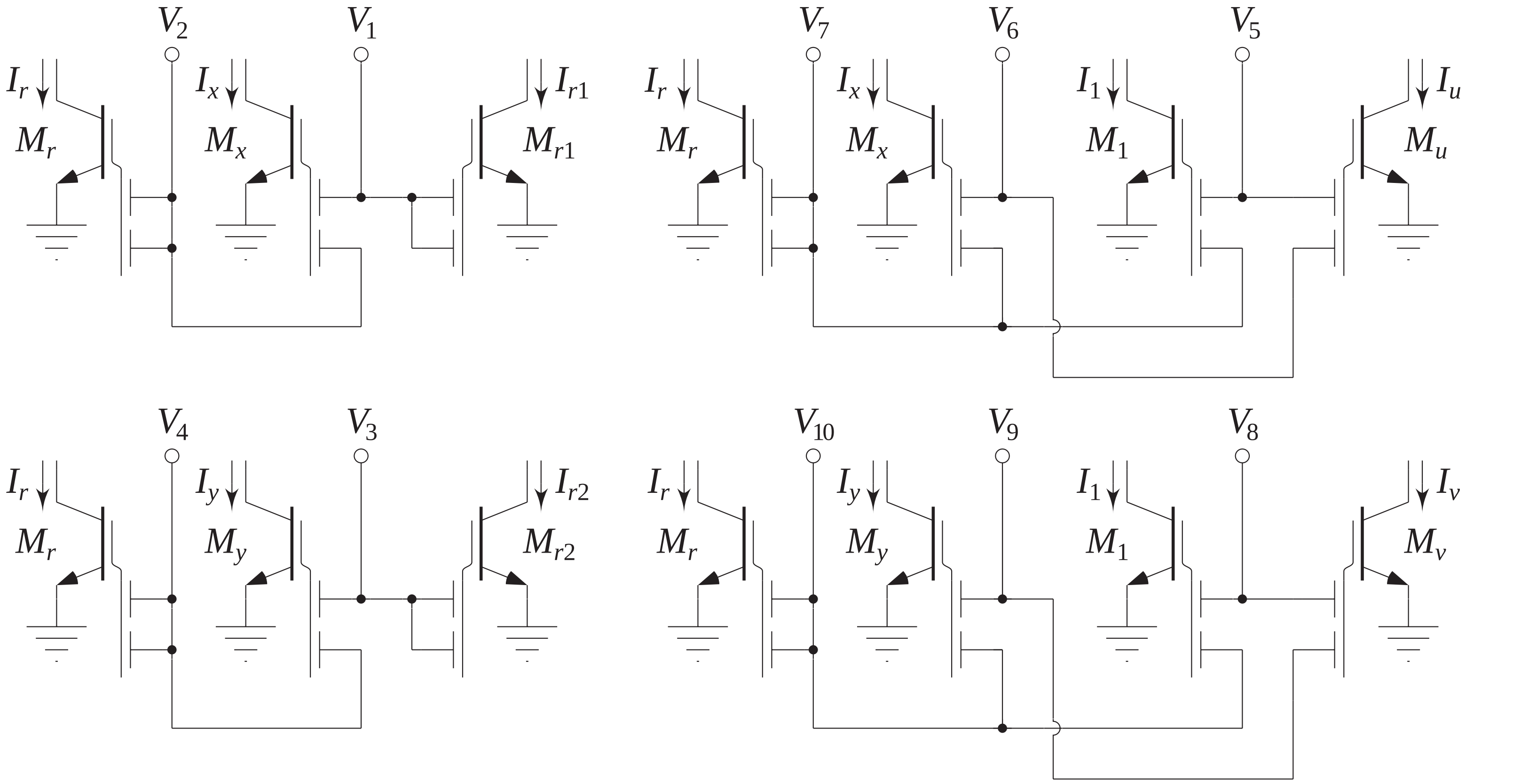
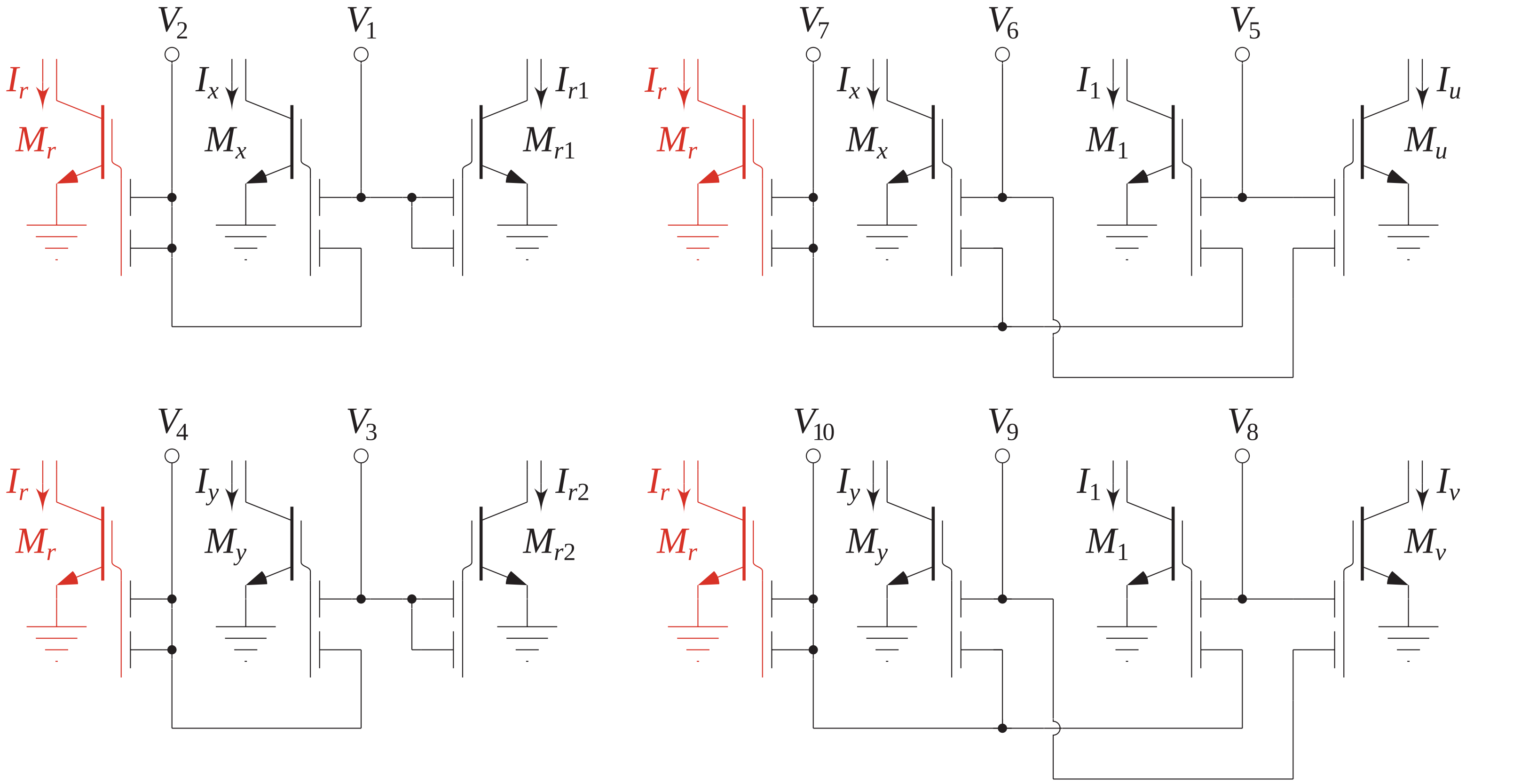


Static MITE Network Synthesis: Vector Normalizer

$$\text{TLP:}\quad I_{r1}I_r = I_x^2 \qquad I_uI_r = I_xI_1 \qquad \text{KCL:}\quad I_r = I_{r1}+I_{r2}$$
$$I_{r2}I_r = I_y^2 \qquad I_vI_r = I_yI_1$$



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Static MITE Network Synthesis: Vector Normalizer

TLP: $I_{r1}I_r = I_x^2 \qquad I_uI_r = I_xI_1$

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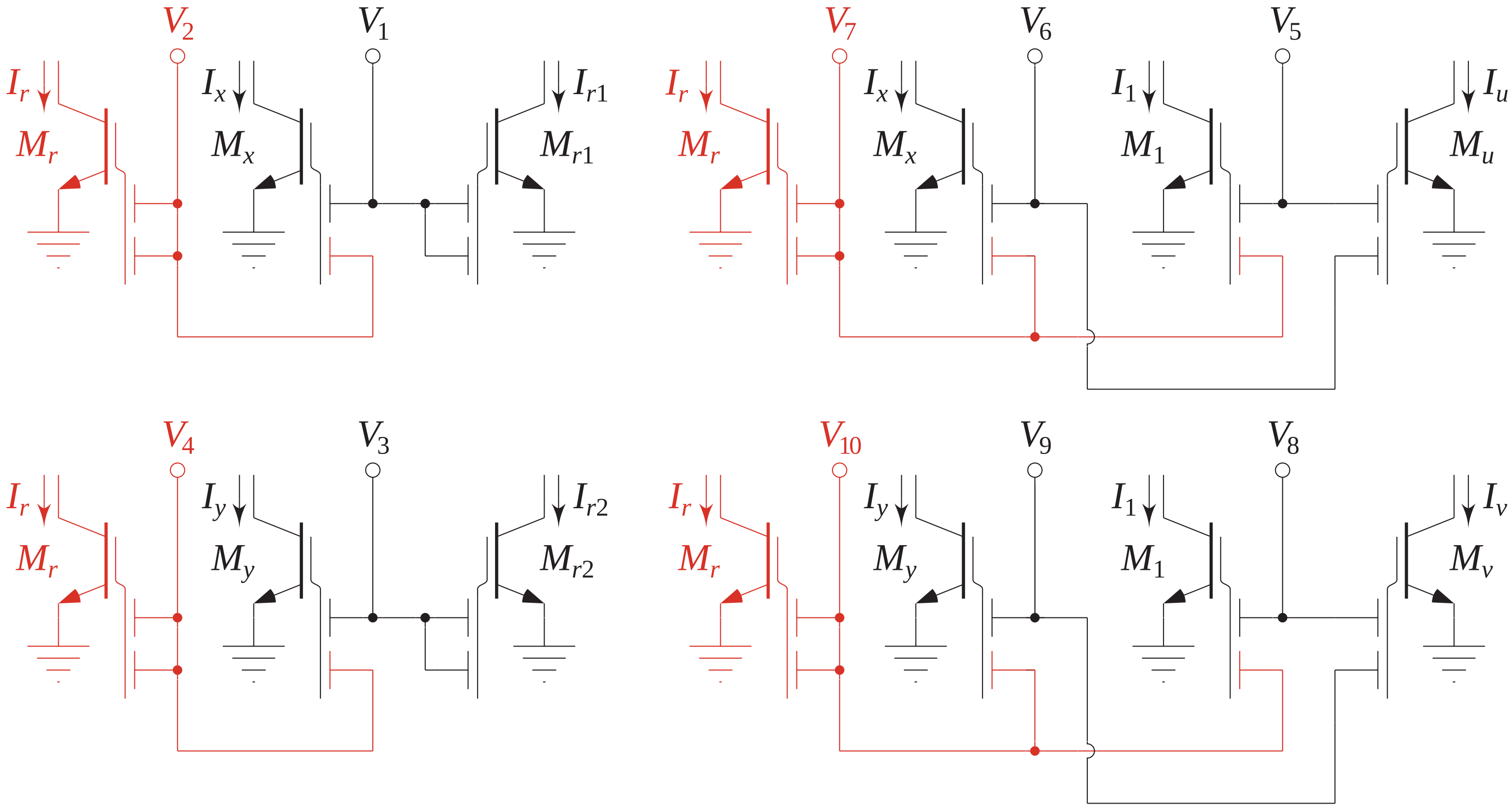

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Static MITE Network Synthesis: Vector Normalizer

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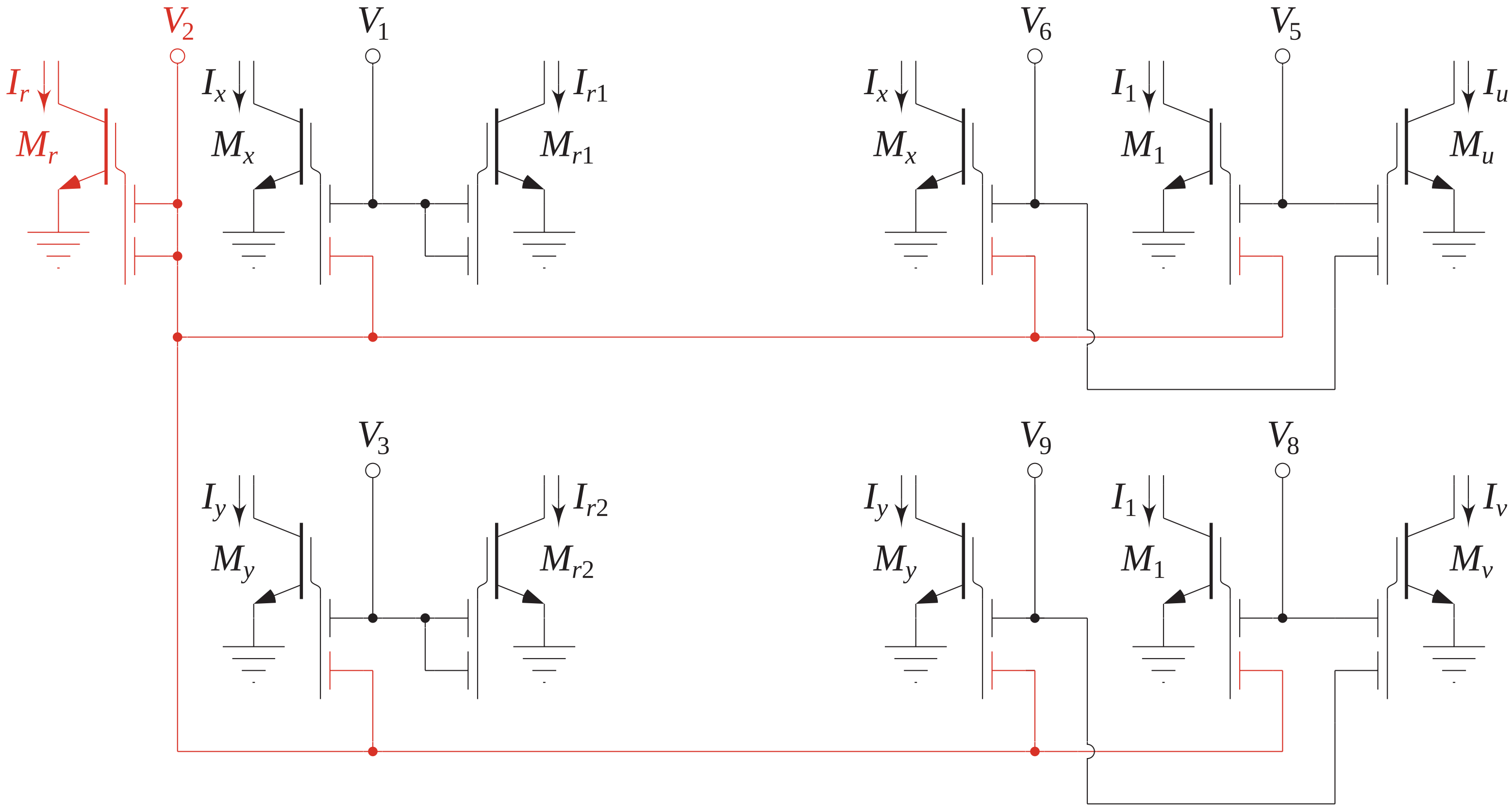

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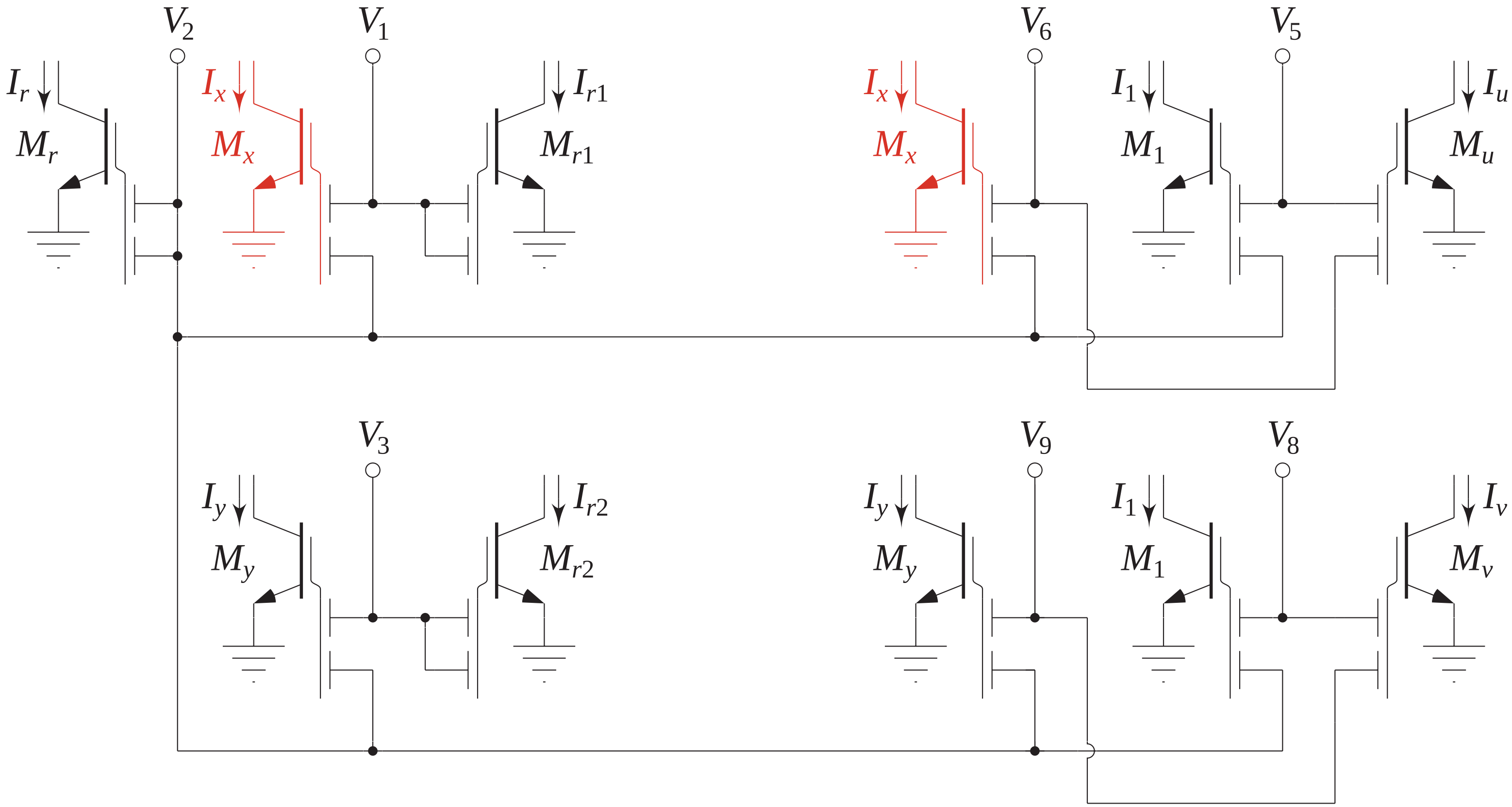

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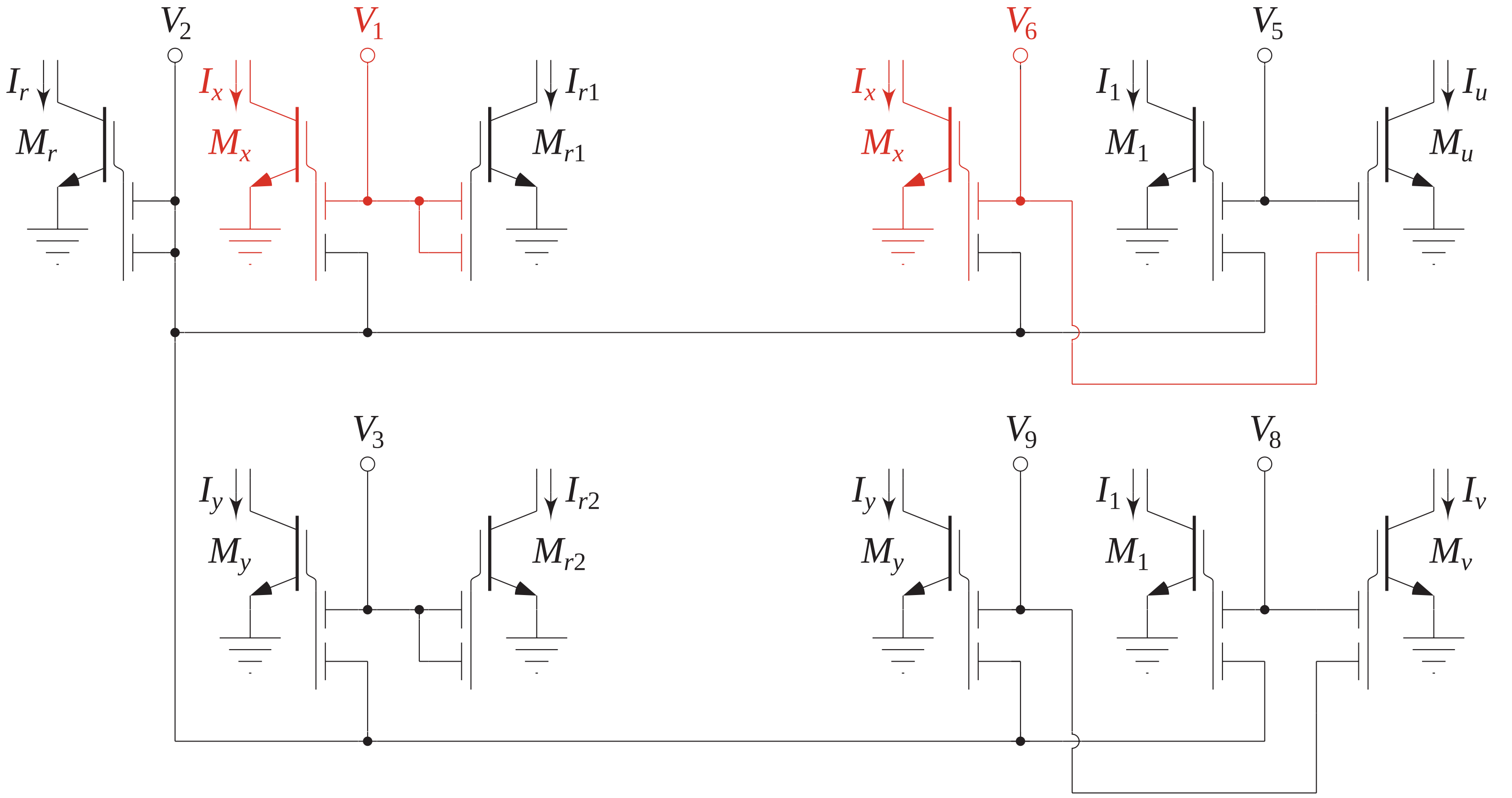

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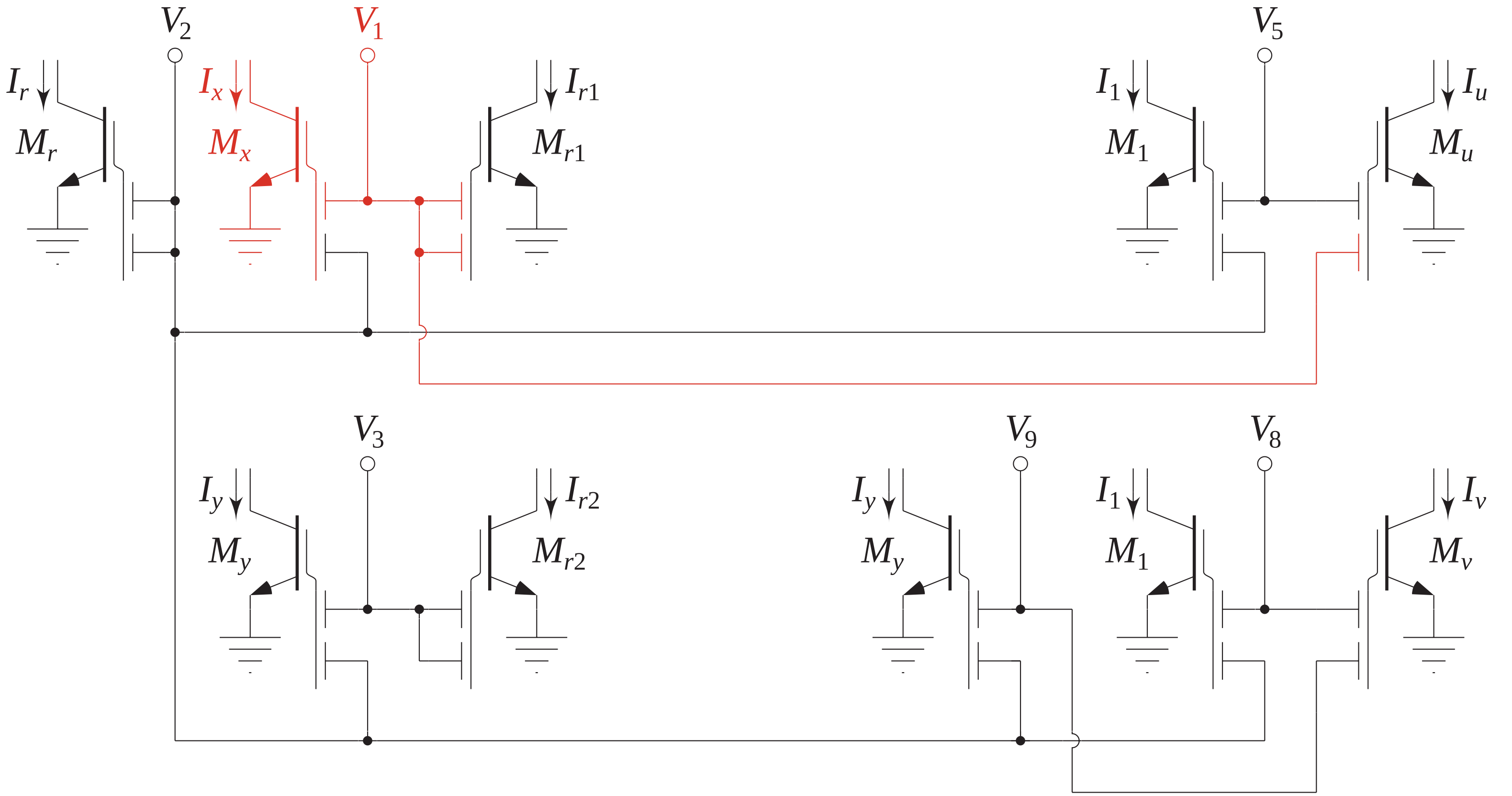

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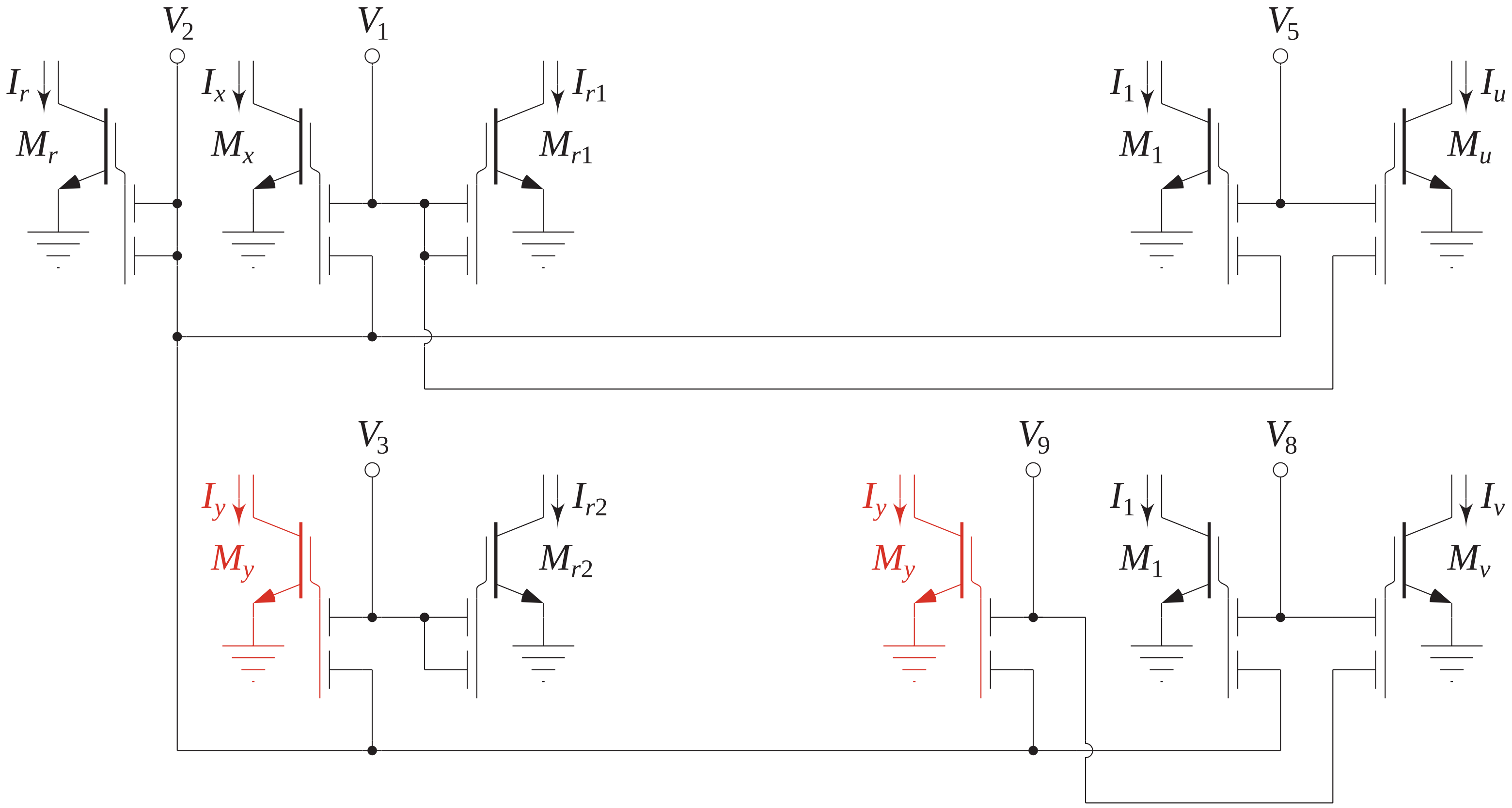

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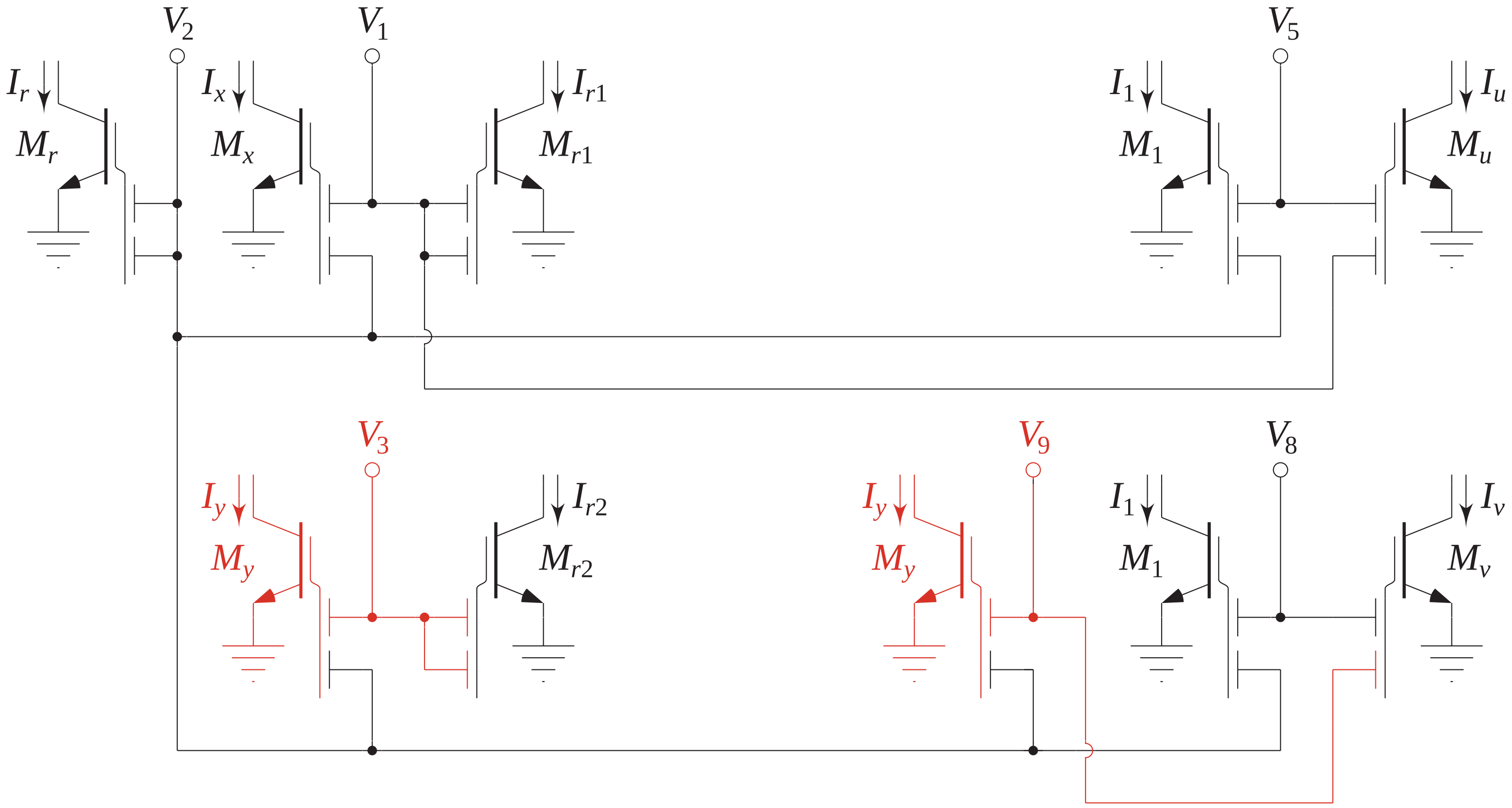
Static MITE Network Synthesis: Vector Normalizer

$$\text{TLP:}\quad I_{r1}I_r = I_x^2 \qquad I_uI_r = I_xI_1 \qquad \text{KCL:}\quad I_r = I_{r1}+I_{r2}$$
$$I_{r2}I_r = I_y^2 \qquad I_vI_r = I_yI_1$$

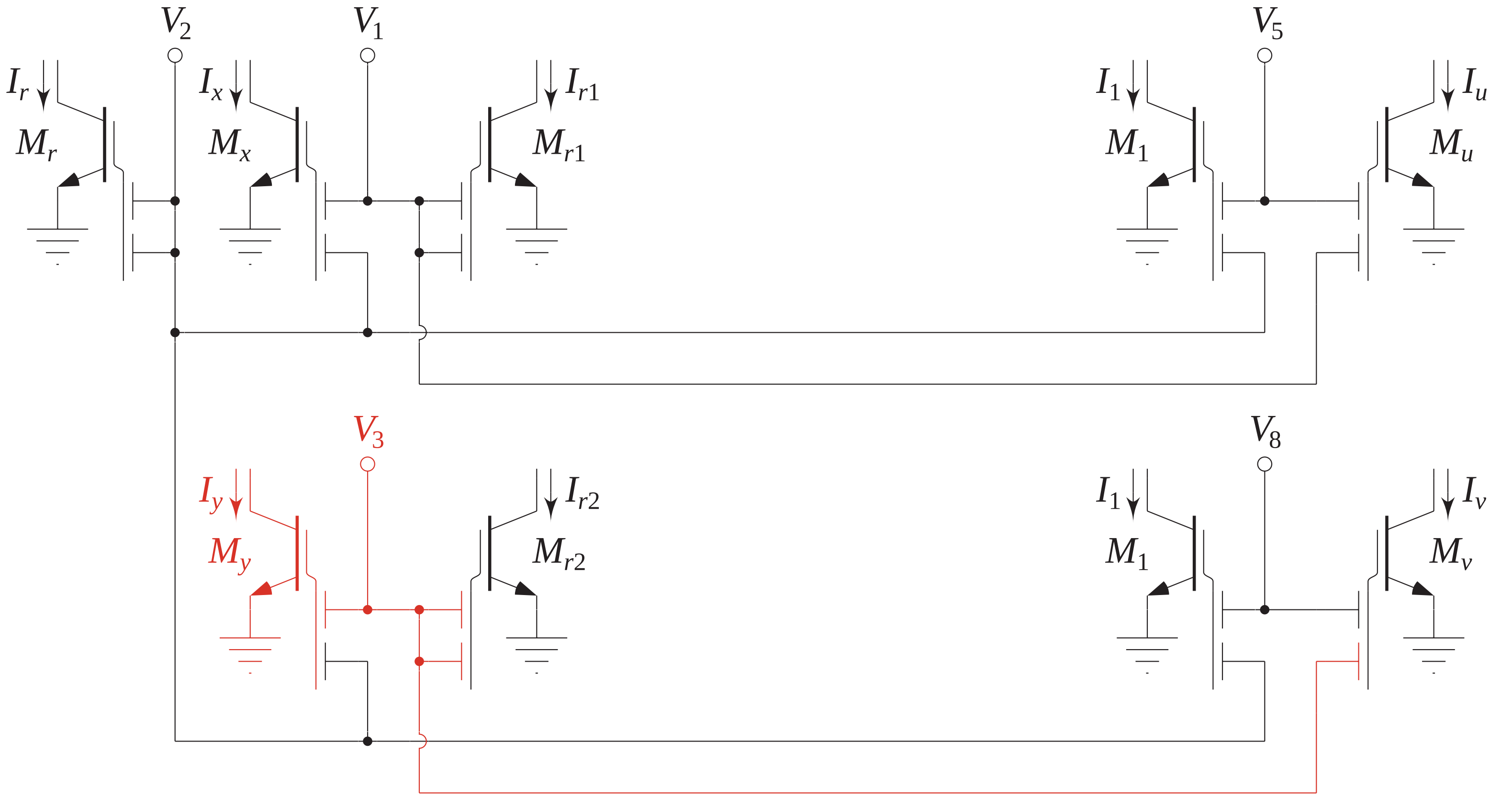


Static MITE Network Synthesis: Vector Normalizer

TLP: $I_{r1}I_r = I_x^2 \qquad I_u I_r = I_x I_1$

$I_{r2}I_r = I_y^2 \qquad I_v I_r = I_y I_1$

KCL: $I_r = I_{r1} + I_{r2}$



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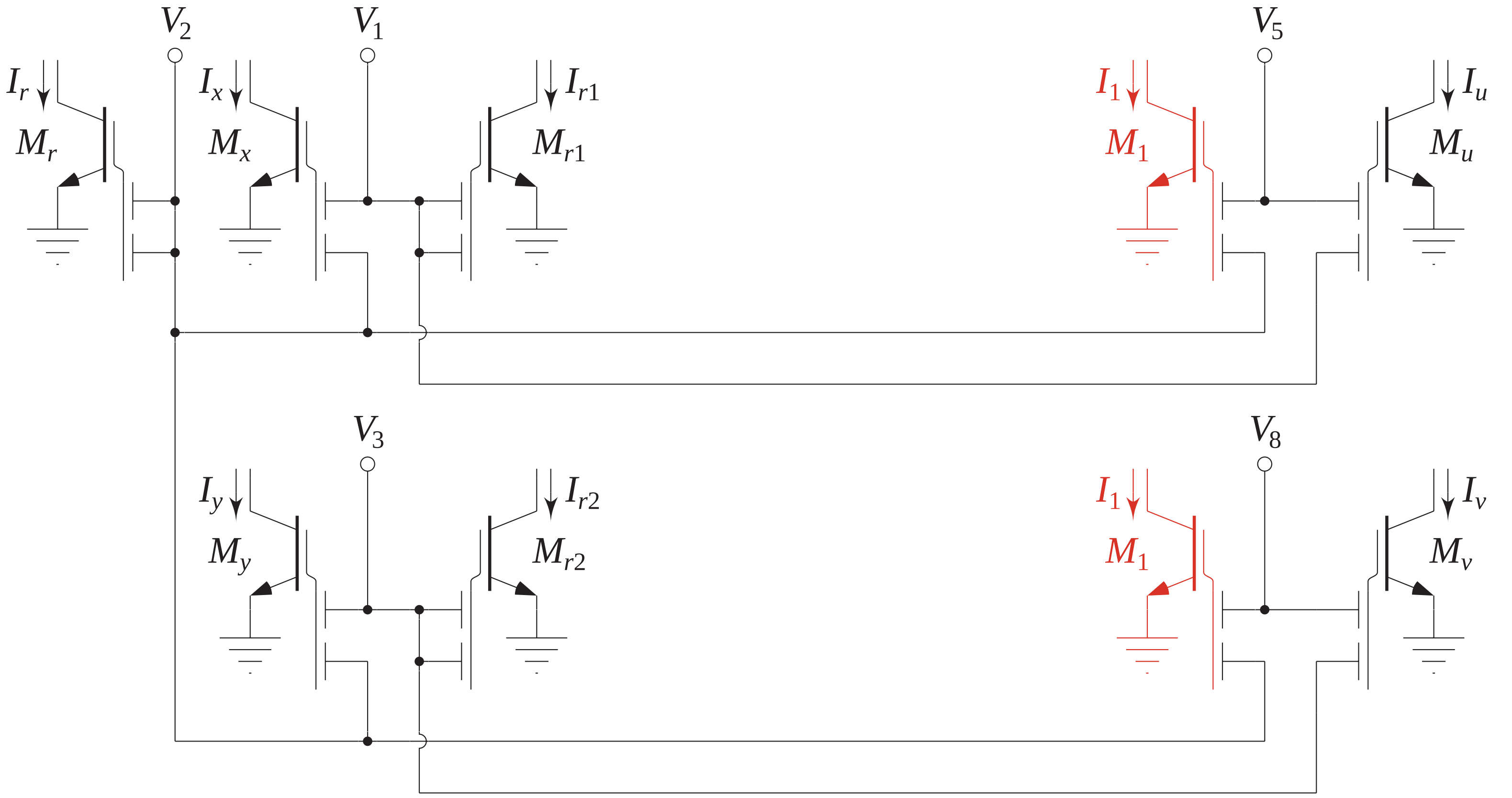

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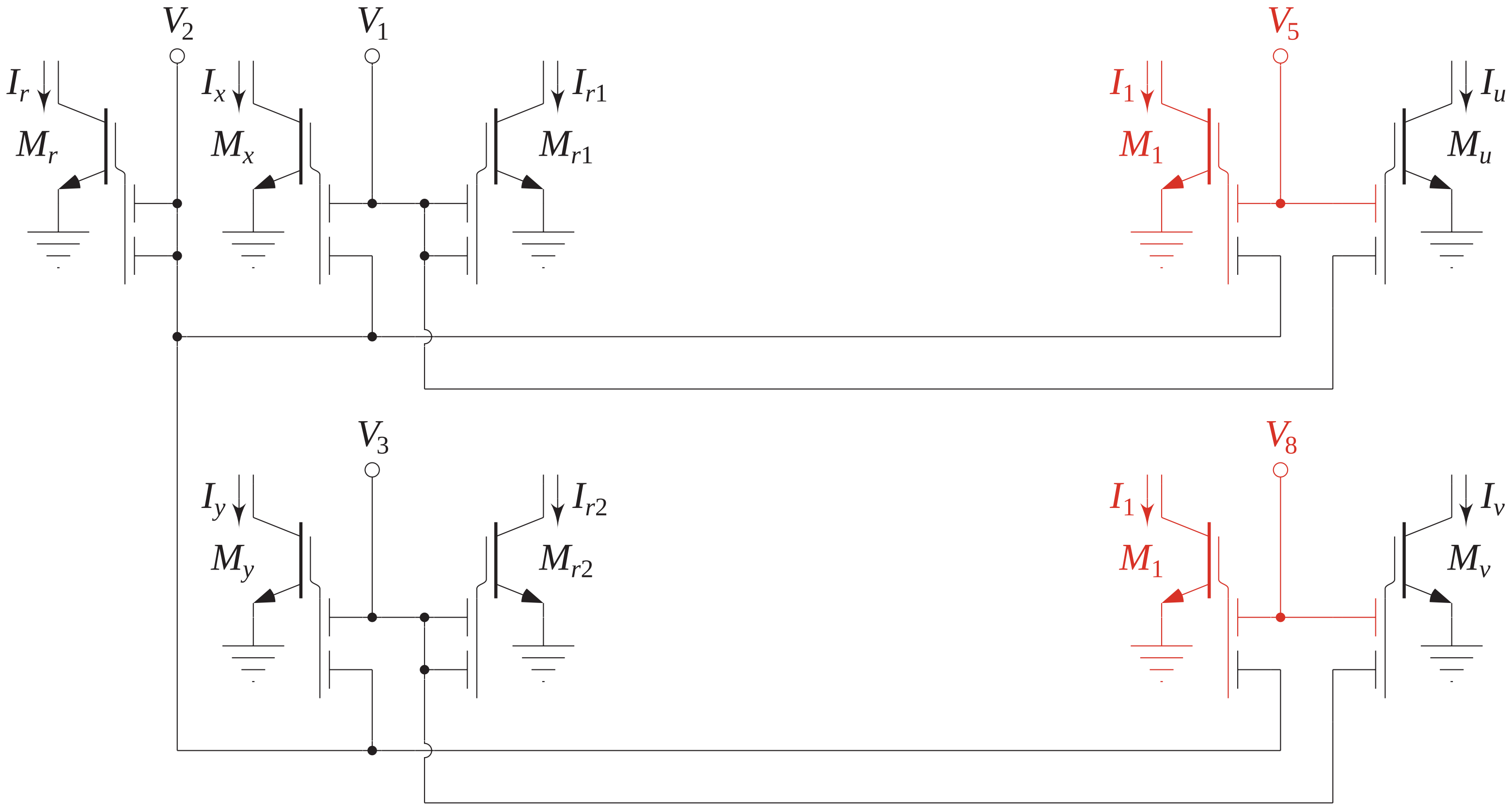

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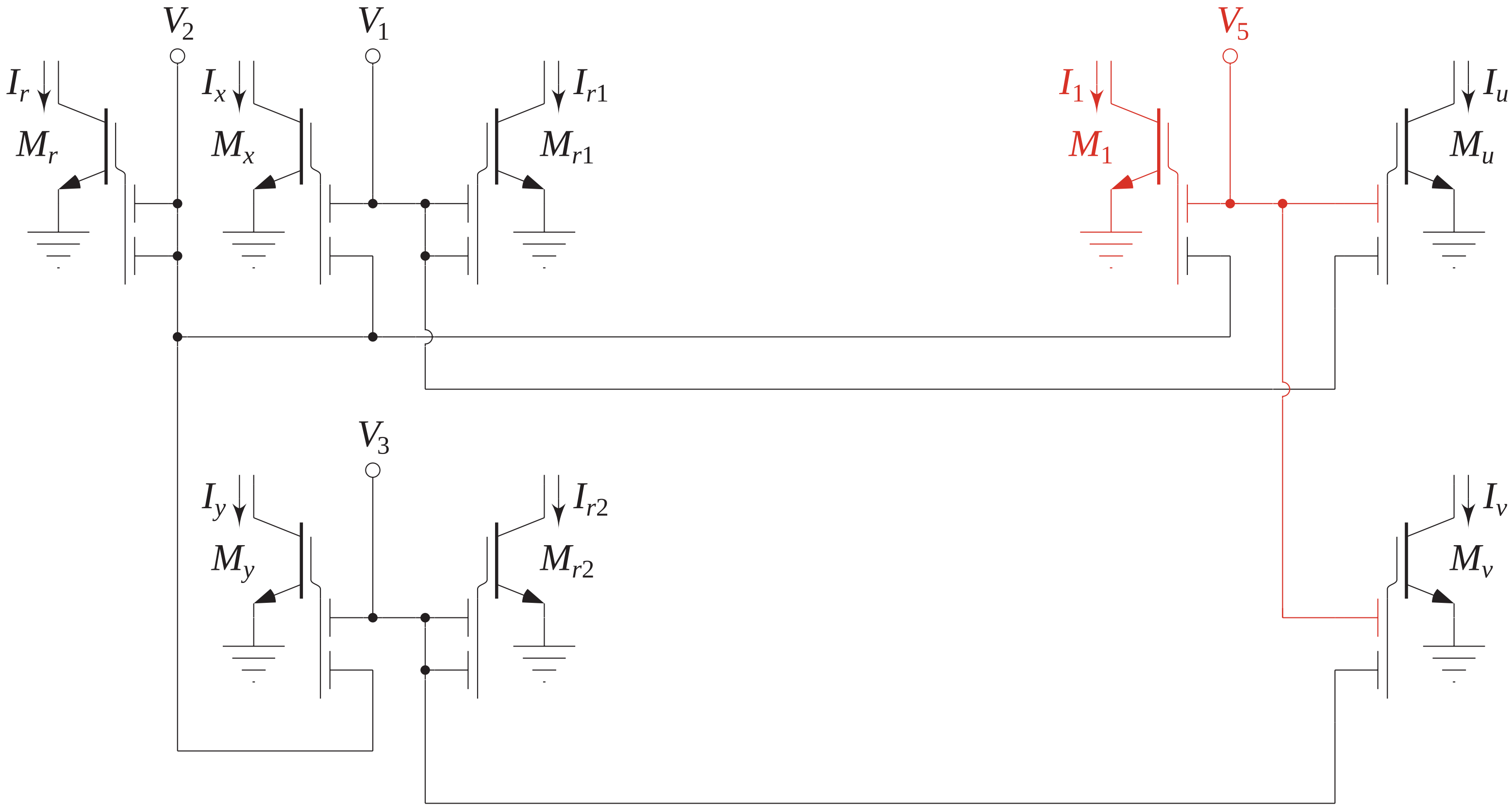

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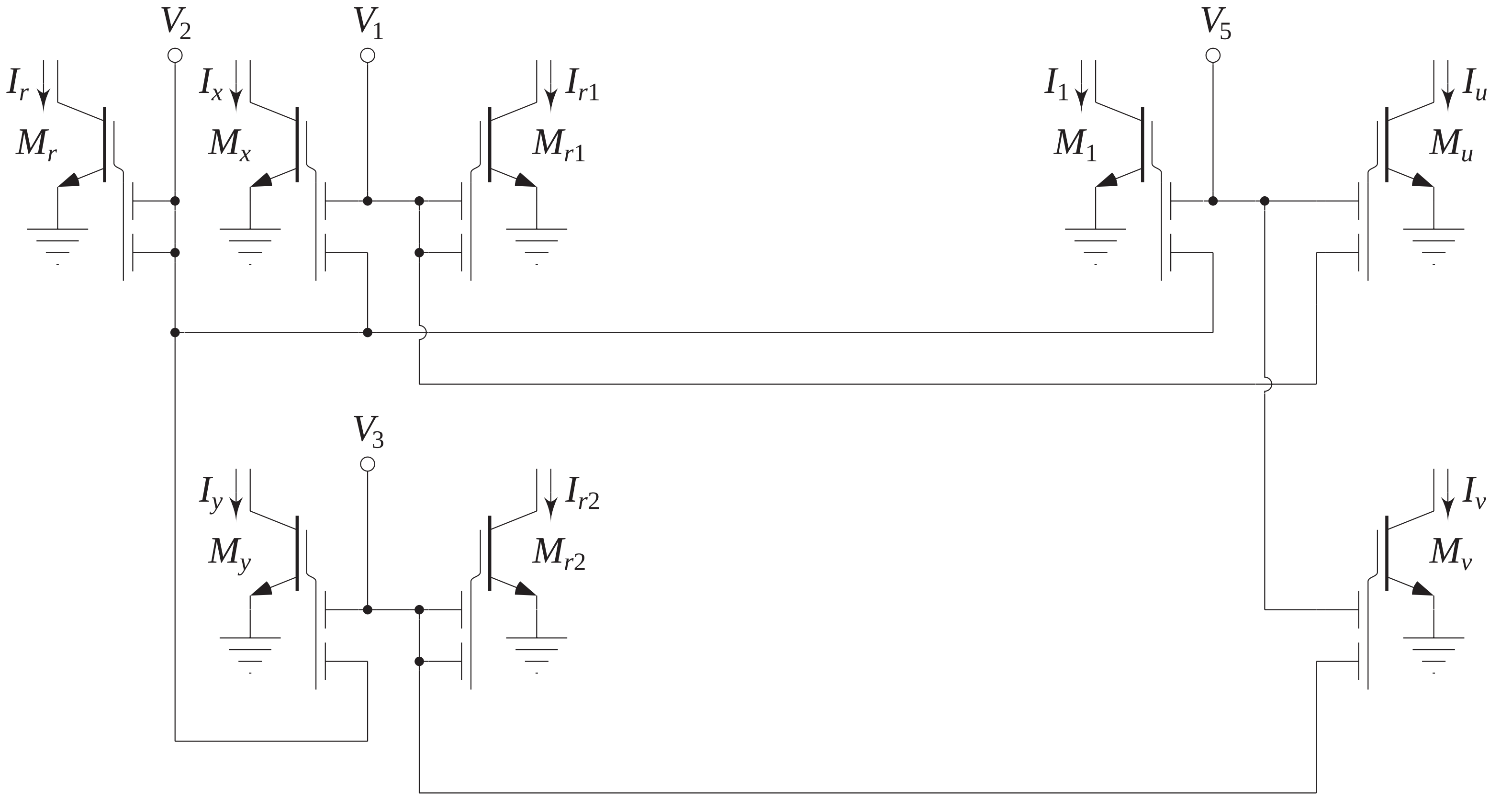

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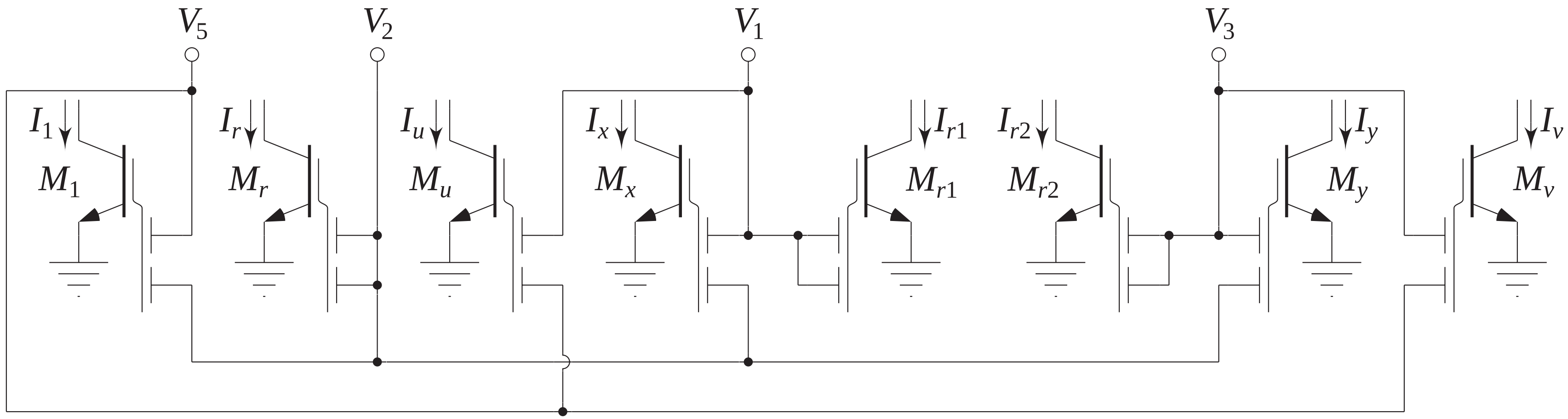

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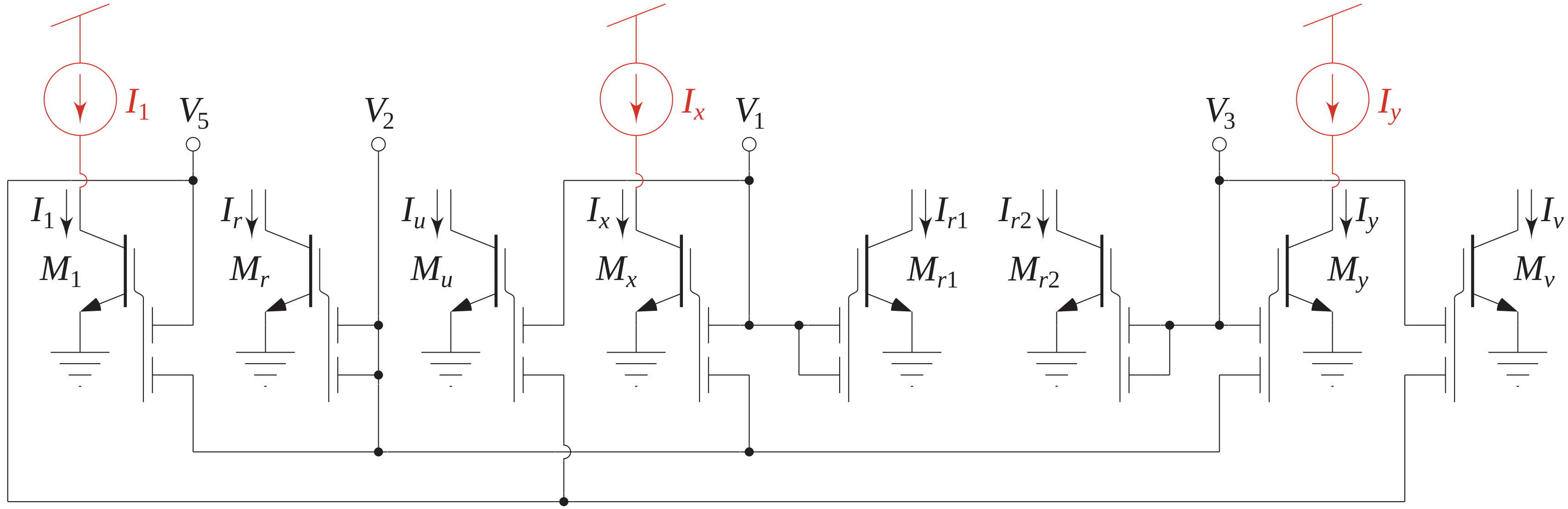

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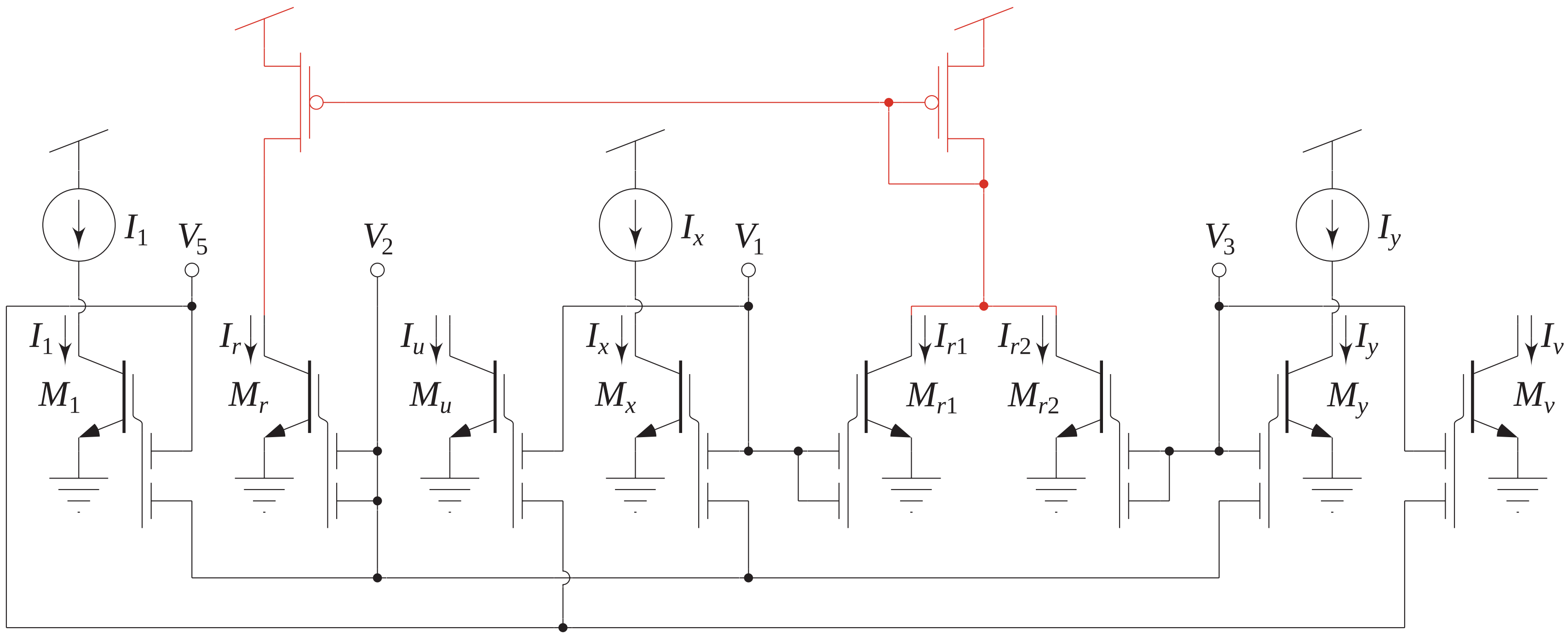

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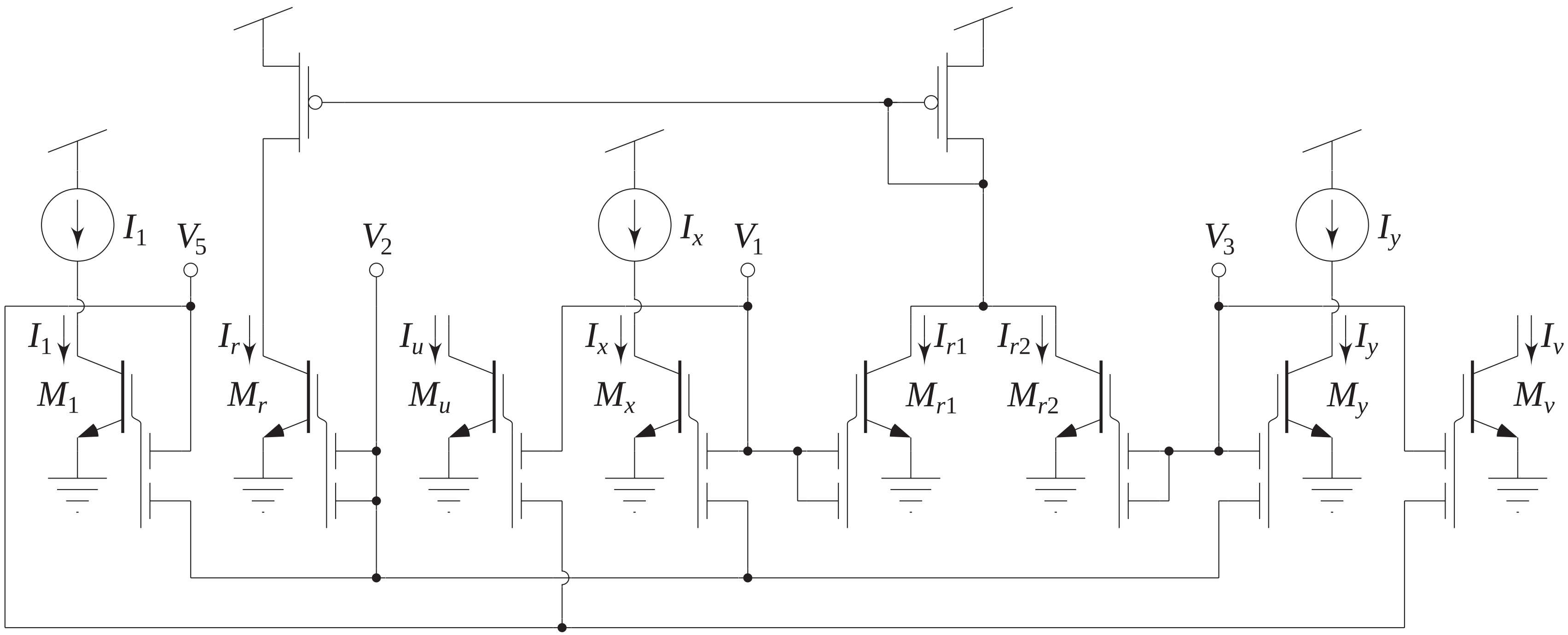

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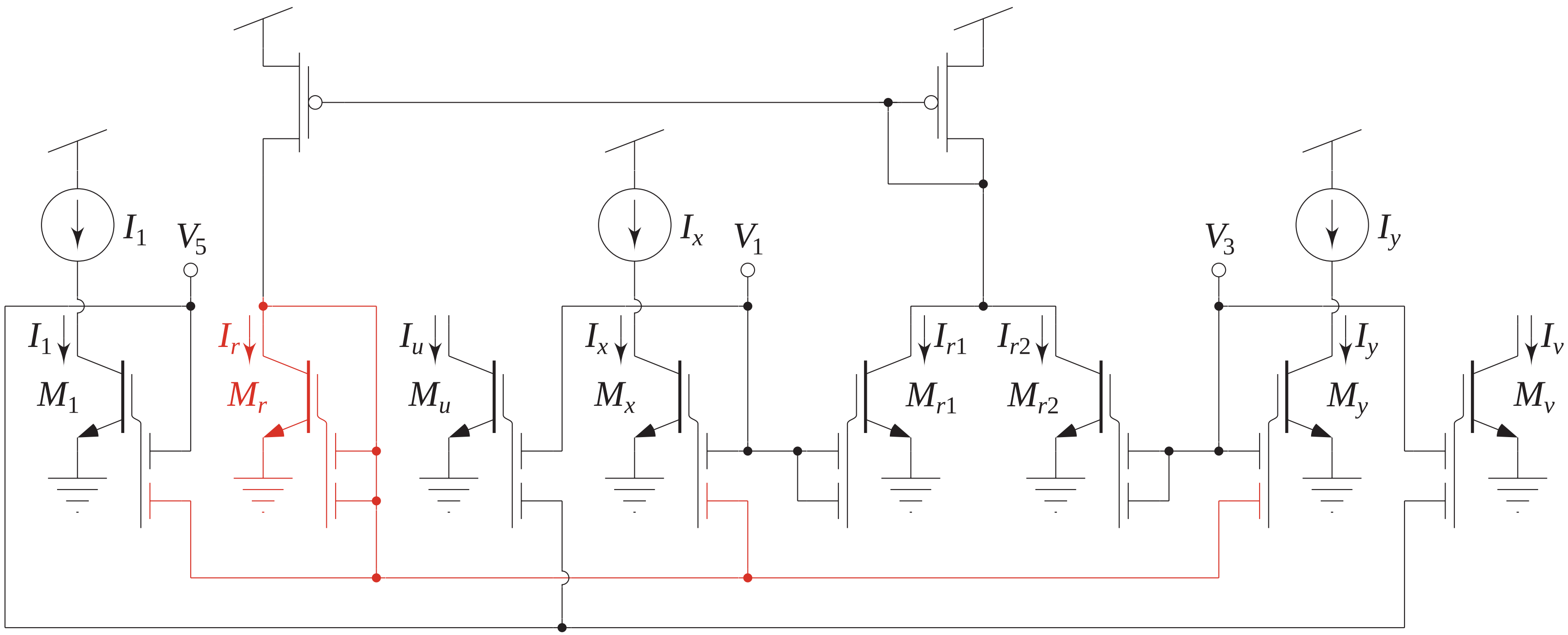

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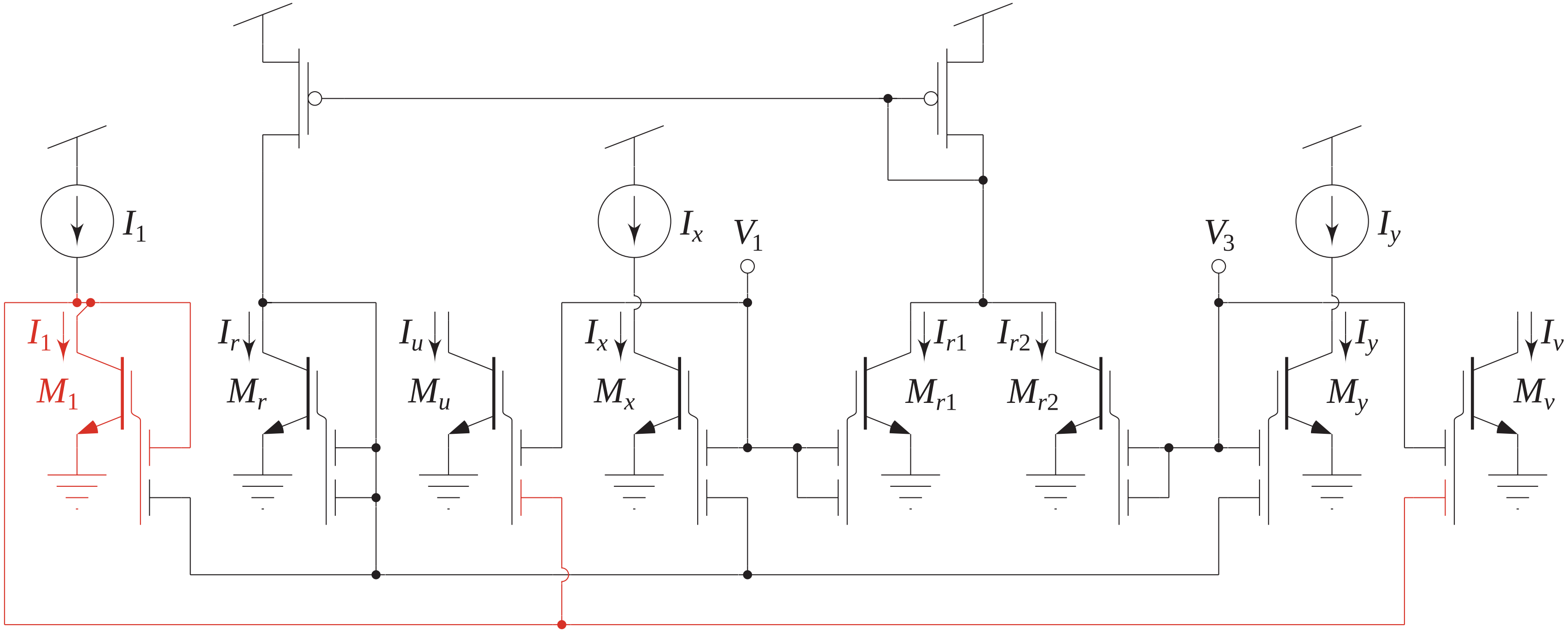

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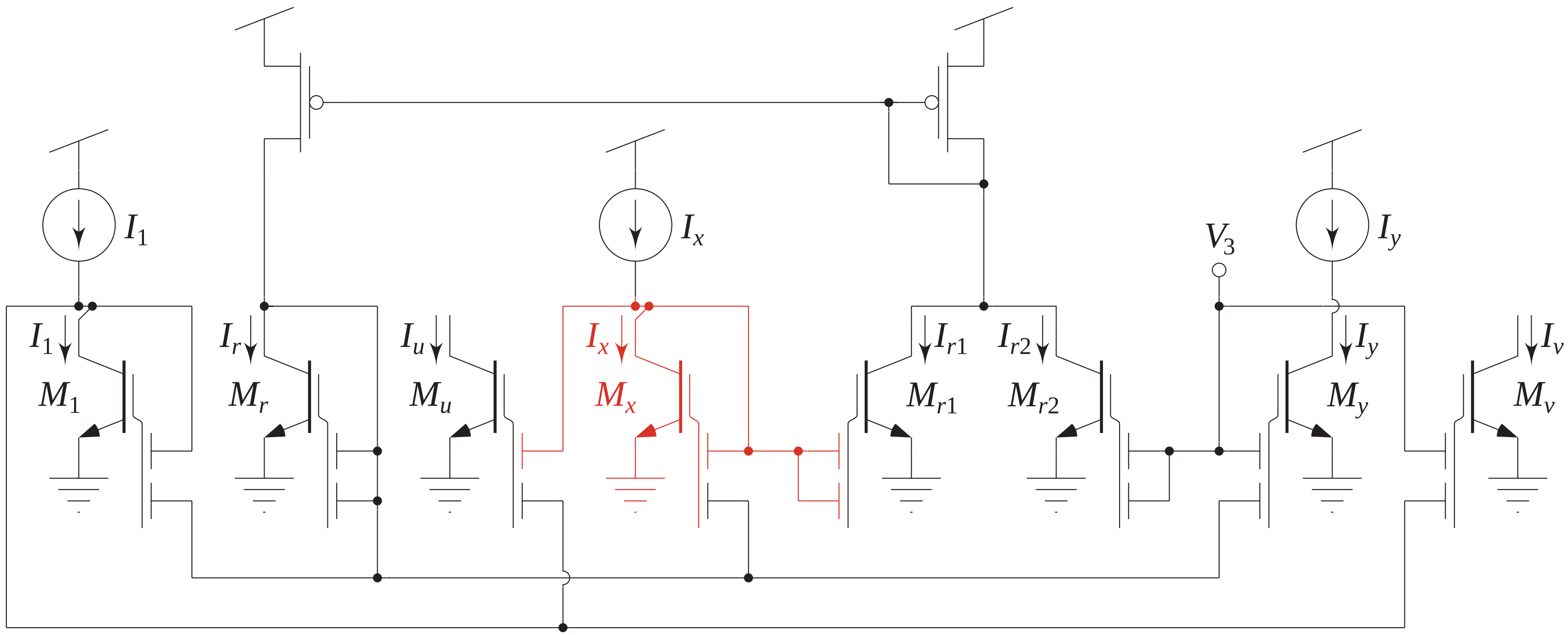

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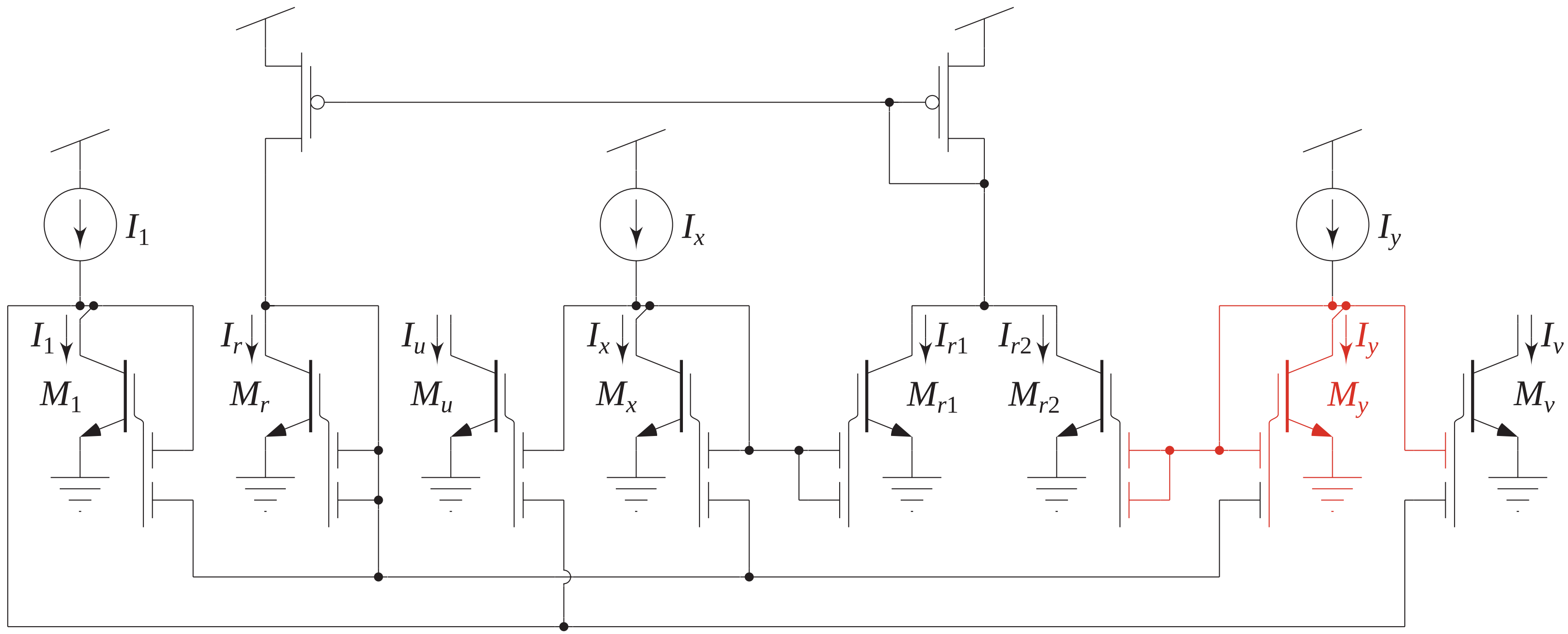

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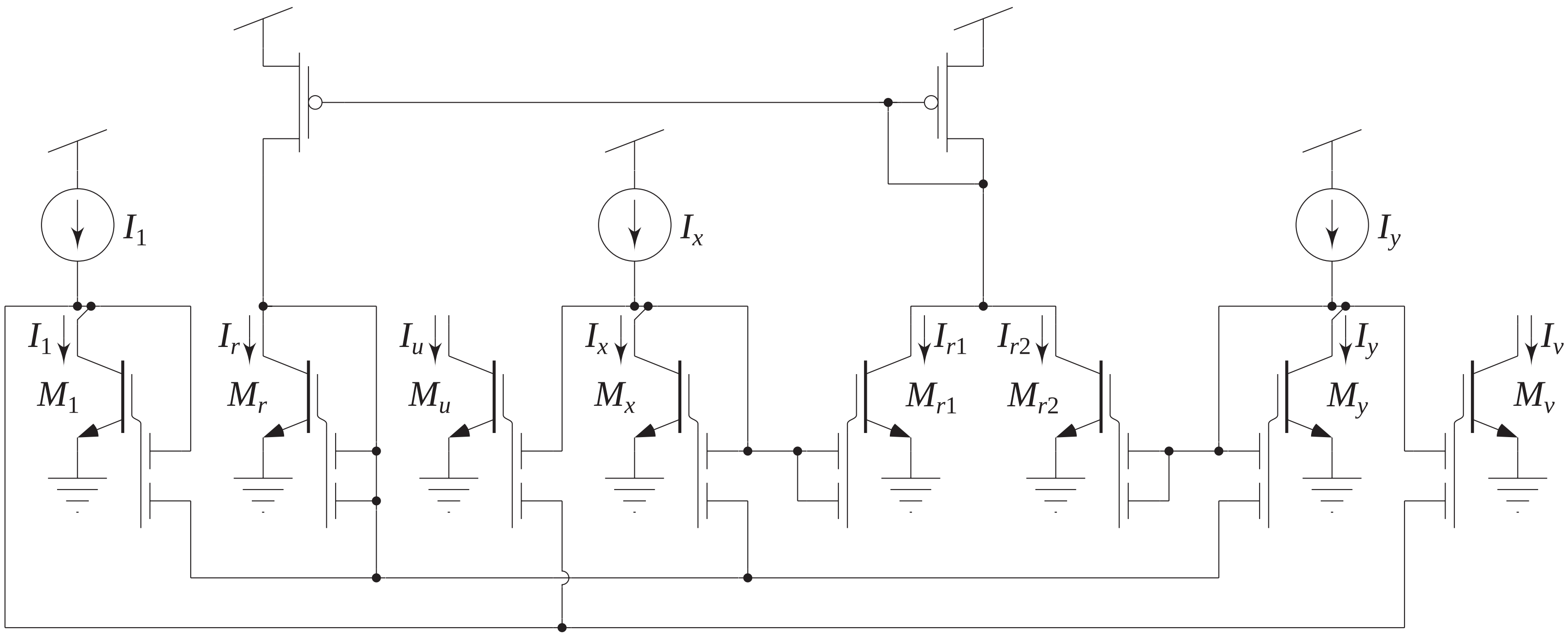
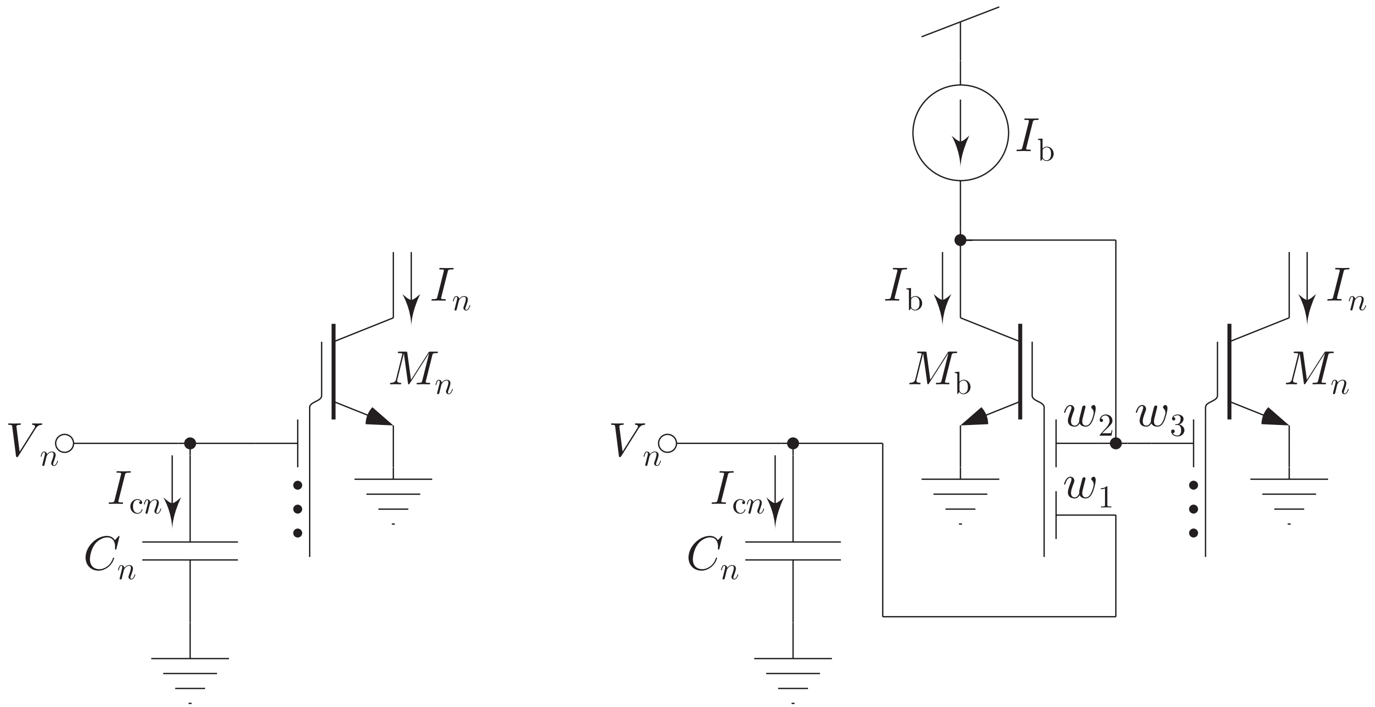


Dynamic MITE Network Synthesis: Output Structures



$$I_n \propto e^{wV_n/U_T}$$

$$\frac{\partial I_n}{\partial V_n} = \frac{w}{U_T} I_n$$

$$I_n \propto e^{-wV_n/U_T}$$

$$\frac{\partial I_n}{\partial V_n} = -\frac{w}{U_T} I_n$$

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Dynamic MITE Network Synthesis: First-Order LPF

Synthesize a first-order low-pass filter described by

$$\tau \frac{dy}{dt} + y = x, \quad \text{where} \quad x > 0.$$

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Substituting these into the ODE, we obtain

$$\tau \frac{d}{dt}\left(\frac{I_y}{I_1}\right) + \frac{I_y}{I_1} = \frac{I_x}{I_1}$$

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$$\tau \frac{d}{dt}\left(\frac{I_y}{I_1}\right) + \frac{I_y}{I_1} = \frac{I_x}{I_1} \quad \Longrightarrow \quad \tau \frac{dI_y}{dt} + I_y = I_x.$$

Dynamic MITE Network Synthesis: First-Order LPF

To implement the time derivative, we introduce a log-compressed voltage state variable, V_y. Using the chain rule, we can express the preceding equation as

$$\tau \frac{\partial I_y}{\partial V_y} \cdot \frac{dV_y}{dt} + I_y = I_x$$

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$$\tau \frac{\partial I_y}{\partial V_y} \cdot \frac{dV_y}{dt} + I_y = I_x \quad \Longrightarrow \quad \tau \left(-\frac{w}{U_\mathrm{T}} I_y \right) \frac{dV_y}{dt} + I_y = I_x$$

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$$\Longrightarrow -\frac{w\tau}{U_\mathrm{T}} \cdot \frac{dV_y}{dt} + 1 = \frac{I_x}{I_y}$$

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$$\Longrightarrow -\frac{I_c}{I_\tau} + 1 = \frac{I_x}{I_y} \quad \Longrightarrow \quad I_c - I_\tau = \frac{I_\tau I_x}{I_y}.$$

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Dynamic MITE Network Synthesis: First-Order LPF

TLP: $I_p I_y = I_x I_\tau$ KCL: $I_p + I_c = I_\tau$

Dynamic MITE Network Synthesis: First-Order LPF

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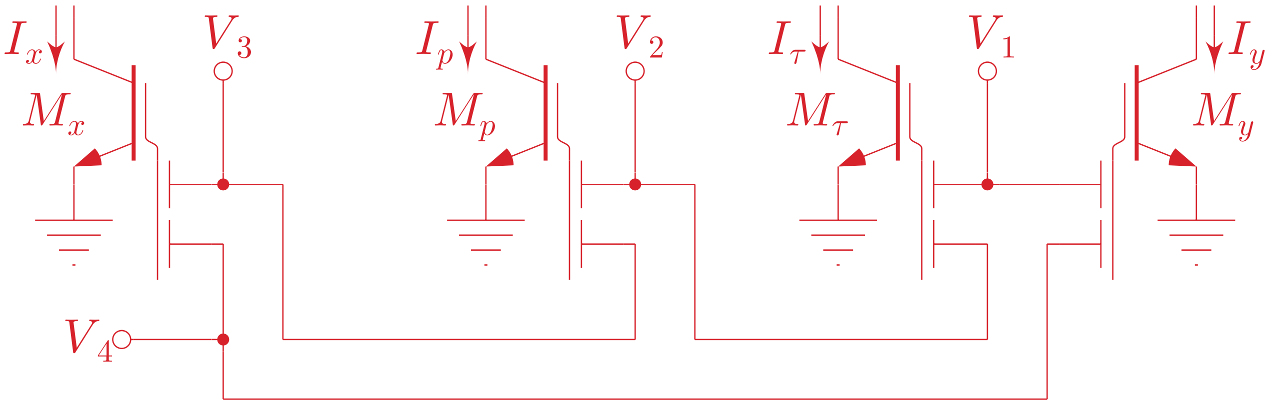

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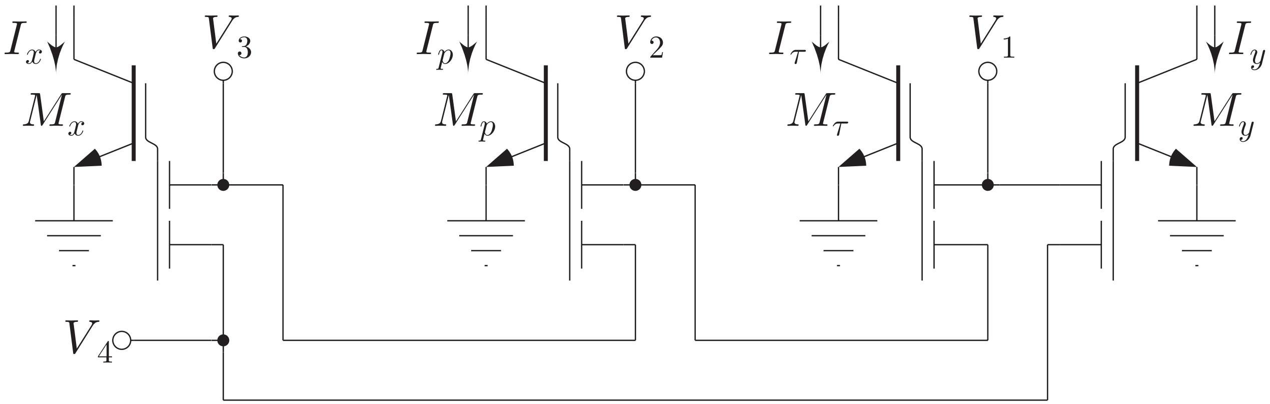

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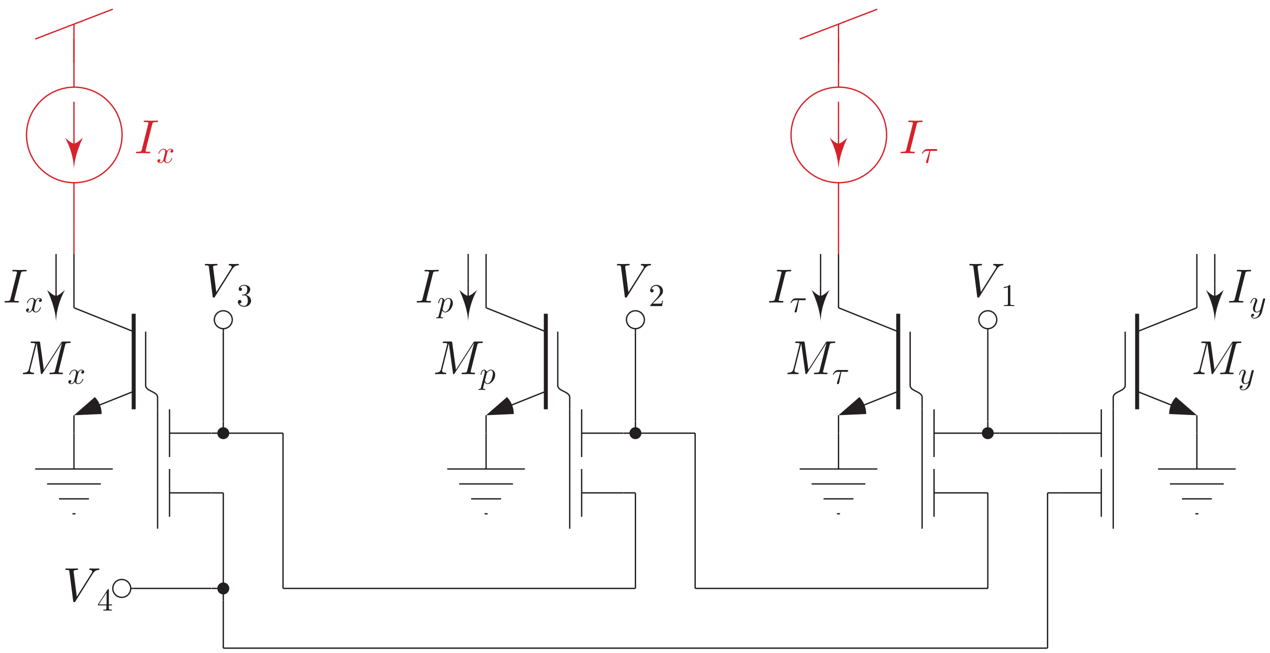

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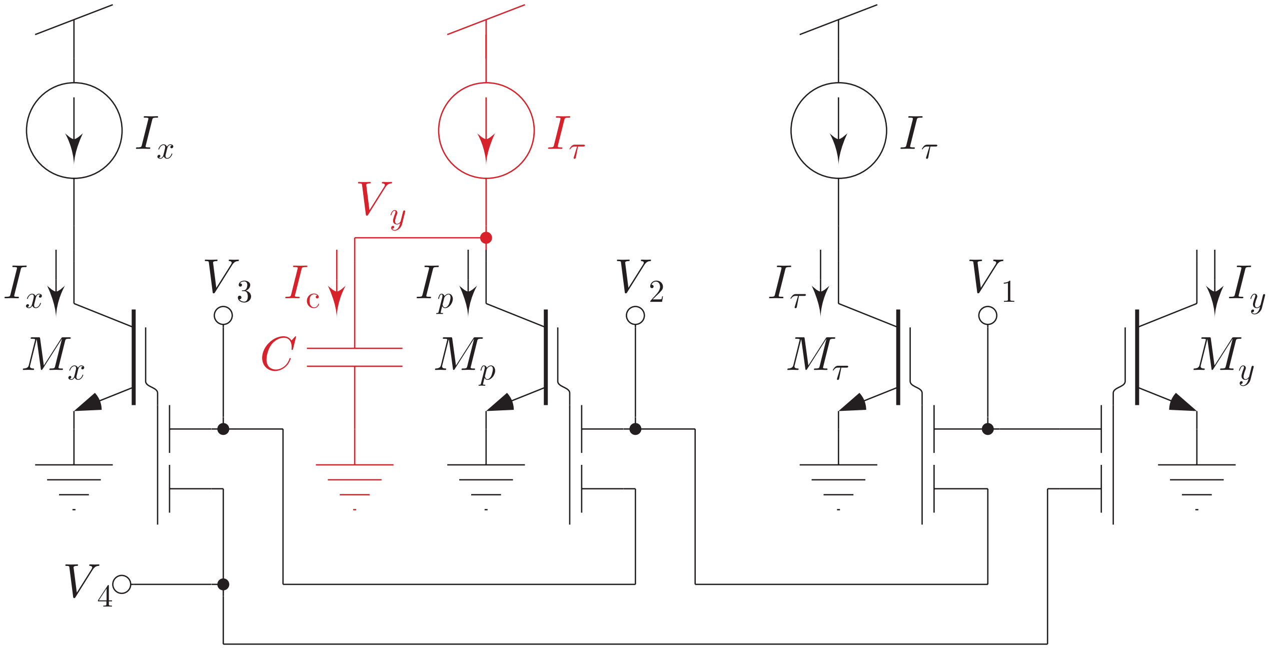

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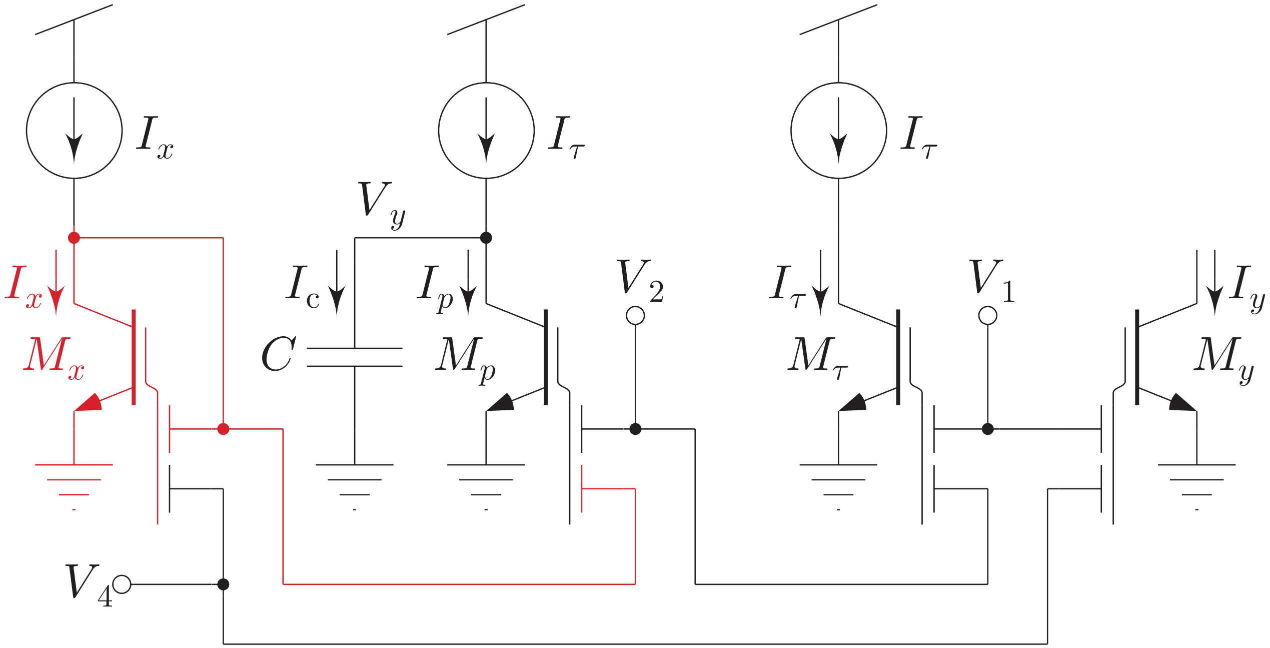

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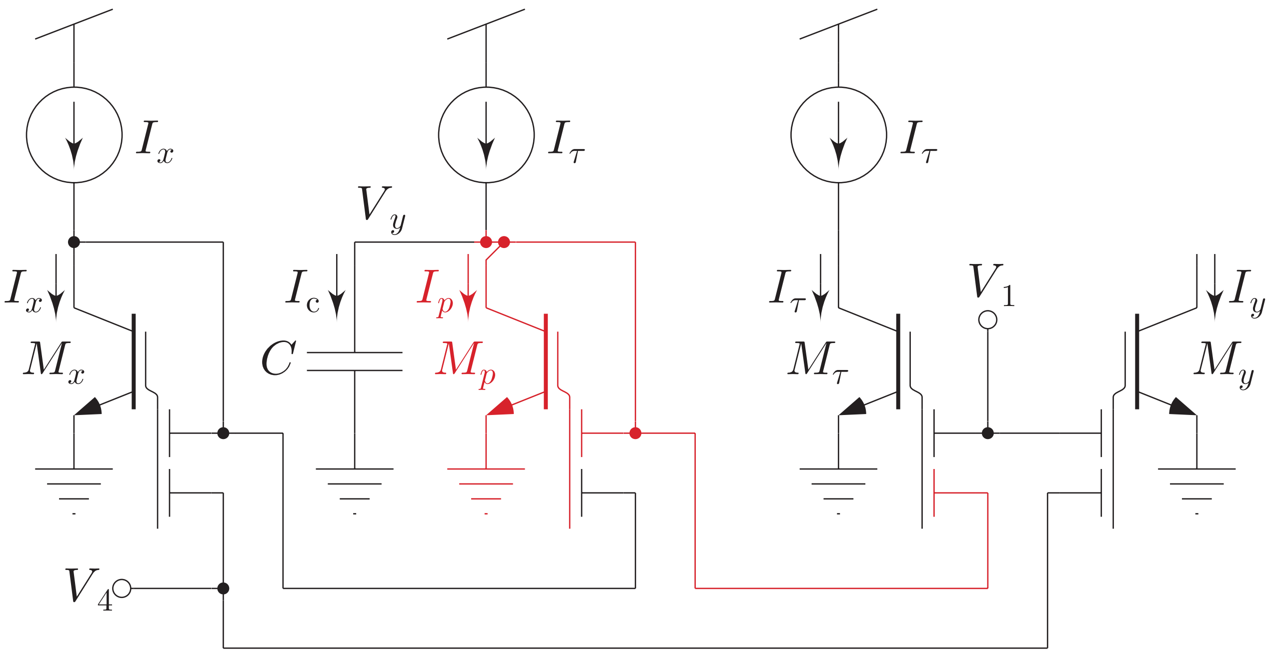

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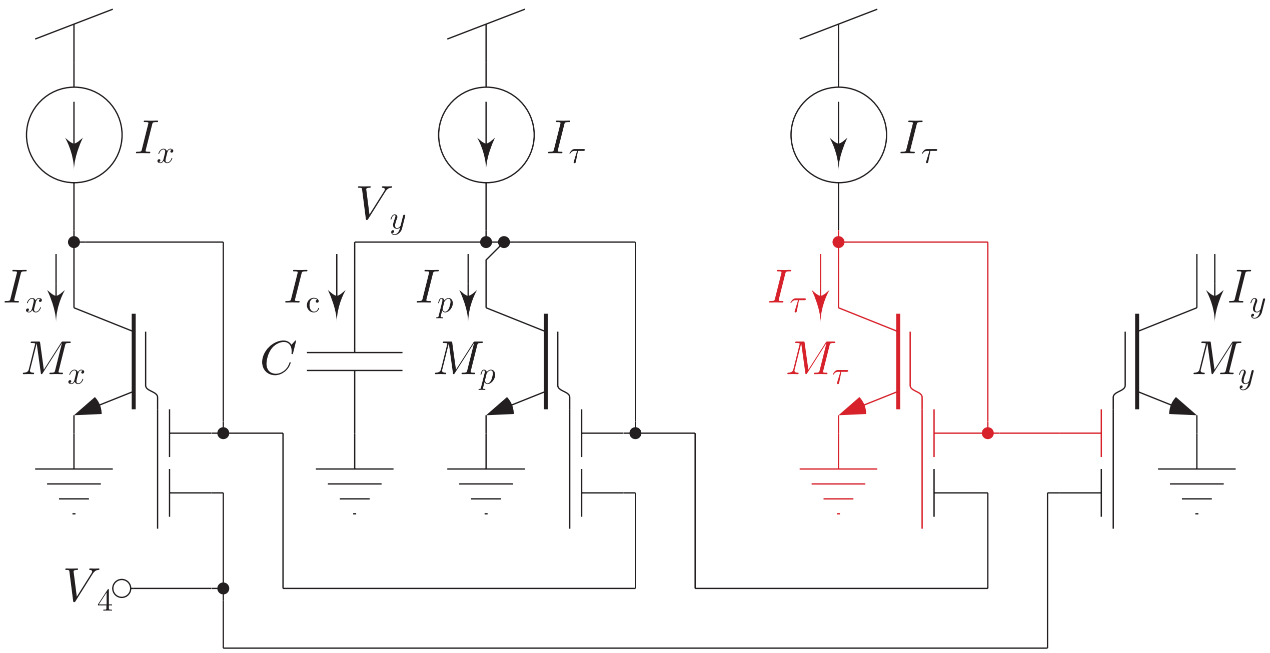

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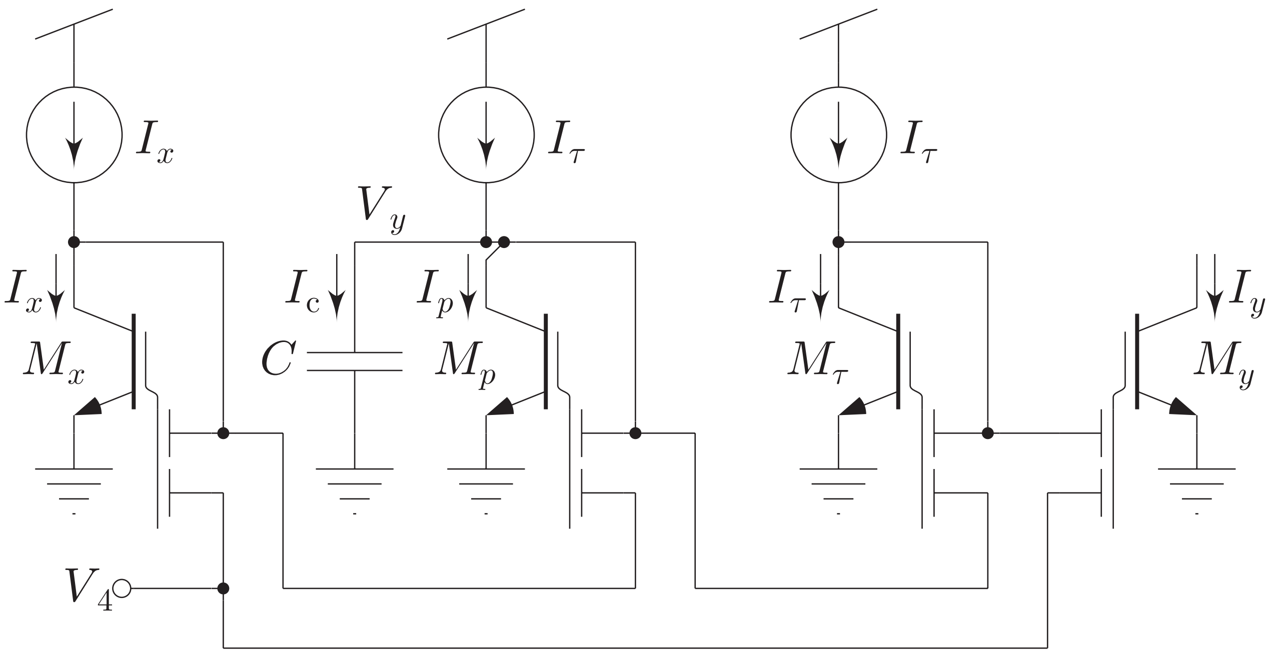

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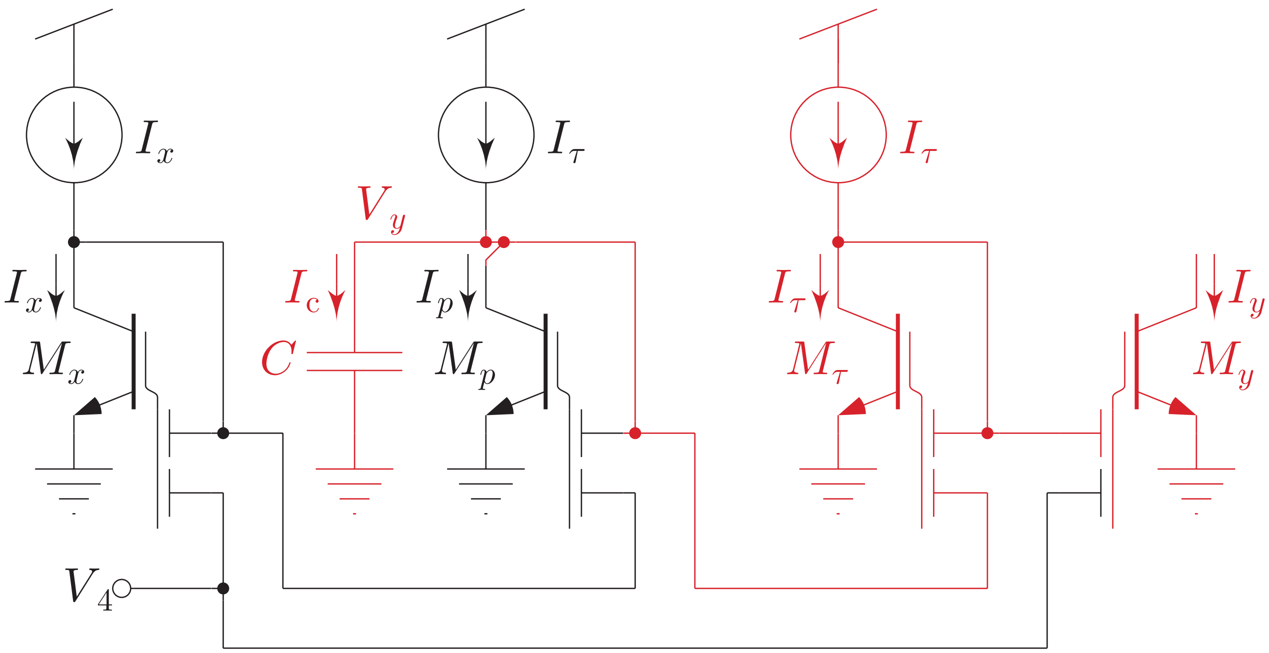

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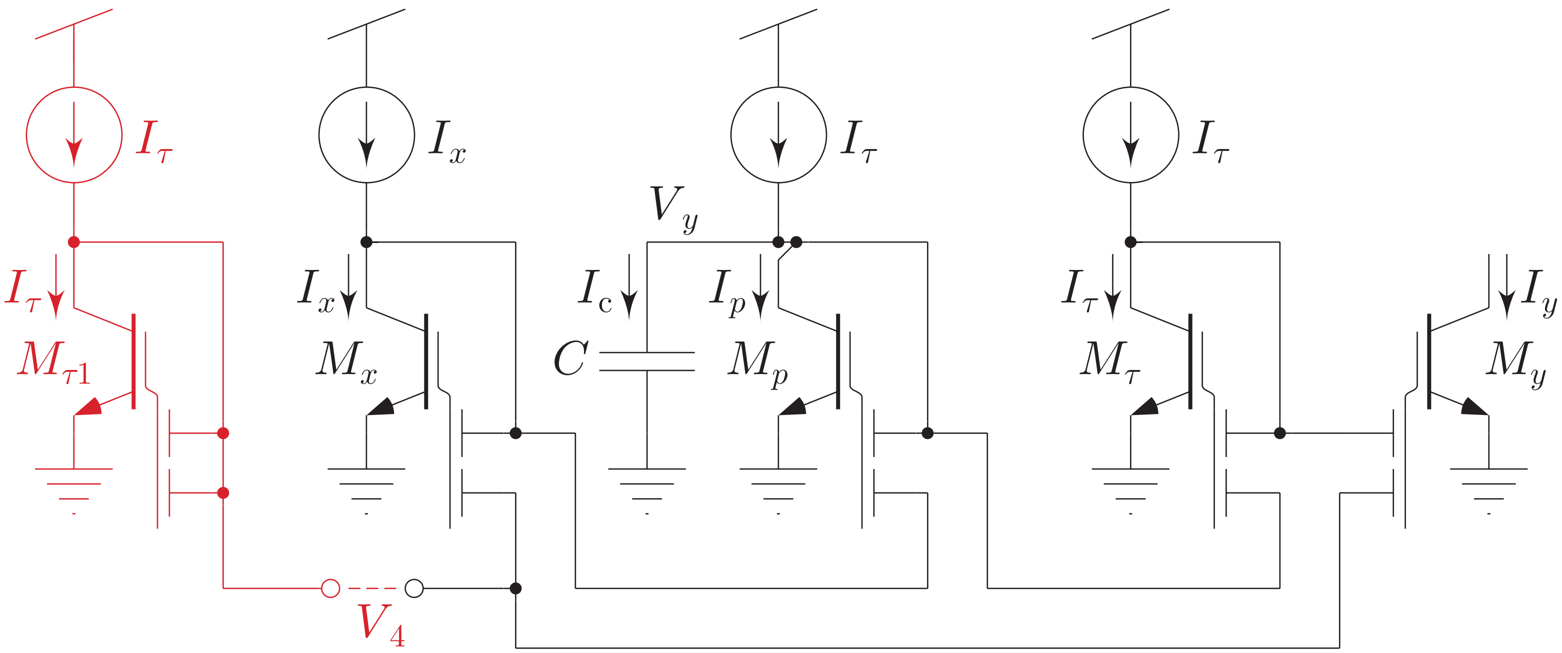

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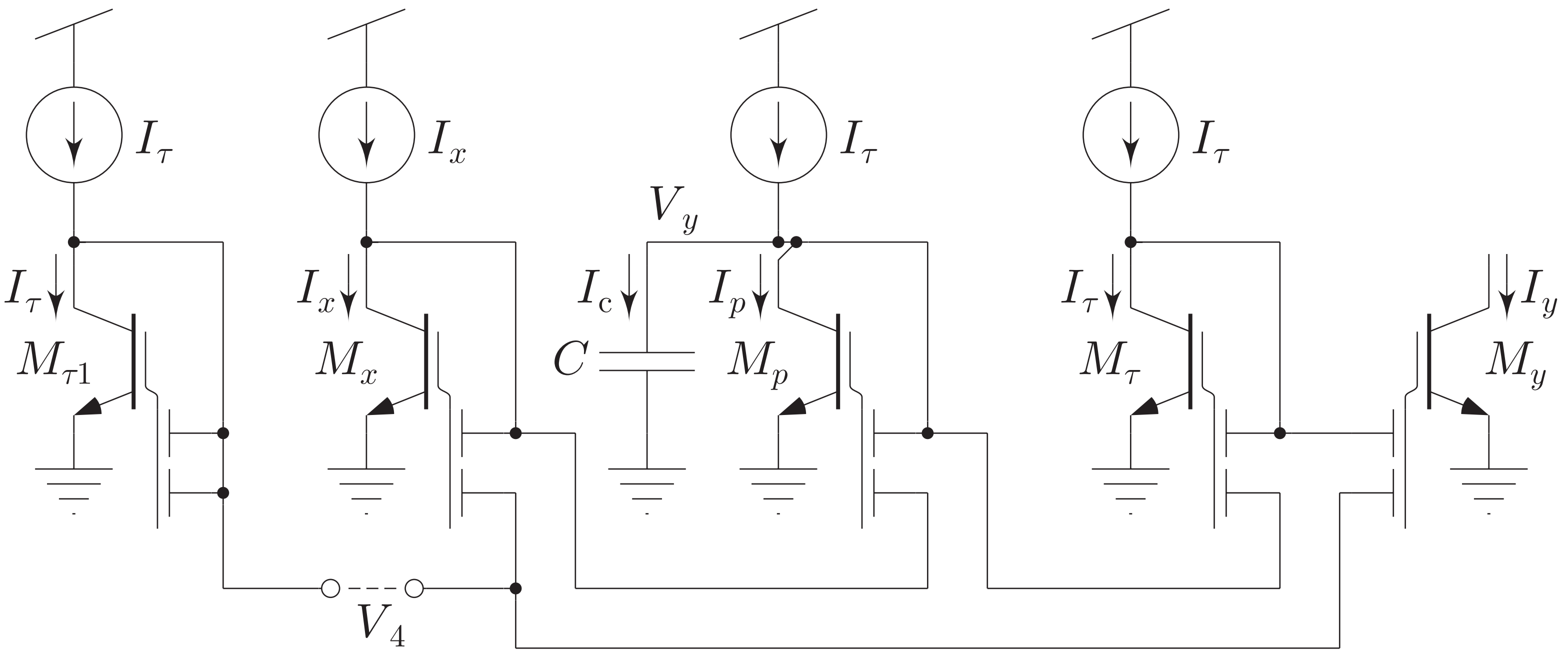

Dynamic MITE Network Synthesis: Second-Order LPF

Synthesize a second-order low-pass filter described by

$$\tau^2 \frac{d^2 y}{dt^2} + \frac{\tau}{Q} \cdot \frac{dy}{dt} + y = x, \quad \text{where} \quad x > 0.$$

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We can decompose this second-order ODE into two coupled first-order ODEs as

$$\tau \frac{d}{dt}\left(\tau \frac{dy}{dt} + \frac{y}{Q} \right) + y = x$$

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$$\tau \frac{d}{dt}\Bigg(\underbrace{\tau \frac{dy}{dt} + \frac{y}{Q}}_{z}\Bigg) + y = x \quad \Longrightarrow \quad \begin{cases} \tau \dfrac{dz}{dt} & = & x - y \\ \tau \dfrac{dy}{dt} & = & z - \dfrac{y}{Q}. \end{cases}$$

Dynamic MITE Network Synthesis: Second-Order LPF

We represent each signal as a ratio of a signal current to the unit current:

$$x \equiv \frac{I_x}{I_1}, \quad y \equiv \frac{I_y}{I_1}, \quad \text{and} \quad z \equiv \frac{I_z}{I_1}.$$

Dynamic MITE Network Synthesis: Second-Order LPF

We represent each signal as a ratio of a signal current to the unit current:

$$x \equiv \frac{I_x}{I_1}, \quad y \equiv \frac{I_y}{I_1}, \quad \text{and} \quad z \equiv \frac{I_z}{I_1}.$$

Substituting these into the pair of ODEs, we obtain

$$\begin{cases} \tau \dfrac{d}{dt}\left(\dfrac{I_z}{I_1}\right) = \dfrac{I_x}{I_1} - \dfrac{I_y}{I_1} \\ \tau \dfrac{d}{dt}\left(\dfrac{I_y}{I_1}\right) = \dfrac{I_z}{I_1} - \dfrac{1}{Q} \cdot \dfrac{I_y}{I_1} \end{cases}$$

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Dynamic MITE Network Synthesis: Second-Order LPF

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Dynamic MITE Network Synthesis: Second-Order LPF

To implement the time derivatives, we introduce log-compressed voltage state variables, V_z and V_y. Using the chain rule, we can express the preceding pair of equations as

$$\begin{cases} \tau \dfrac{\partial I_z}{\partial V_z} \cdot \dfrac{dV_z}{dt} & = & I_x - I_y \\ \tau \dfrac{\partial I_y}{\partial V_y} \cdot \dfrac{dV_y}{dt} & = & I_z - \dfrac{I_y}{Q} \end{cases}$$

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Dynamic MITE Network Synthesis: Second-Order LPF

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$$\Longrightarrow \begin{cases} \dfrac{w\tau}{U_\mathrm{T}} \cdot \dfrac{dV_z}{dt} = \dfrac{I_y}{I_z} - \dfrac{I_x}{I_z} \\ \dfrac{w\tau}{U_\mathrm{T}} \cdot \dfrac{dV_y}{dt} = \dfrac{1}{Q} - \dfrac{I_z}{I_y} \end{cases}$$

Dynamic MITE Network Synthesis: Second-Order LPF

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Dynamic MITE Network Synthesis: Second-Order LPF

By introducing

$$I_\tau \equiv \frac{CU_\mathrm{T}}{w\tau}, \quad I_{cz} \equiv C\frac{dV_z}{dt}, \quad \text{and} \quad I_{cy} \equiv C\frac{dV_y}{dt},$$

we can express this pair of equations as

$$\begin{cases} \dfrac{I_{cz}}{I_\tau} = \dfrac{I_y}{I_z} - \dfrac{I_x}{I_z} \\ \dfrac{I_{cy}}{I_\tau} = \dfrac{1}{Q} - \dfrac{I_z}{I_y} \end{cases}$$

Dynamic MITE Network Synthesis: Second-Order LPF

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we can express this pair of equations as

$$\left\{ \begin{array}{rcl} \dfrac{I_{cz}}{I_\tau} & = & \dfrac{I_y}{I_z} - \dfrac{I_x}{I_z} \\ \dfrac{I_{cy}}{I_\tau} & = & \dfrac{1}{Q} - \dfrac{I_z}{I_y} \end{array} \right. \implies \left\{ \begin{array}{rcl} I_{cz} & = & \dfrac{I_y I_\tau}{I_z} - \dfrac{I_x I_\tau}{I_z} \\ I_{cy} & = & \dfrac{I_\tau}{Q} - \dfrac{I_z I_\tau}{I_y} \end{array} \right.$$

Dynamic MITE Network Synthesis: Second-Order LPF

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we can express this pair of equations as

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where we have further introduced

$$I_w \equiv \frac{I_y I_\tau}{I_z}, \quad I_{pz} \equiv \frac{I_x I_\tau}{I_z}, \quad \text{and} \quad I_{py} \equiv \frac{I_z I_\tau}{I_y}.$$

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\qquad I_y I_{py} = I_z I_\tau$

$I_z I_w = I_y I_\tau$

KCL: $I_{pz} + I_{cz} = I_w$

$I_{py} + I_{cy} = I_\tau / Q$

Dynamic MITE Network Synthesis: Second-Order LPF

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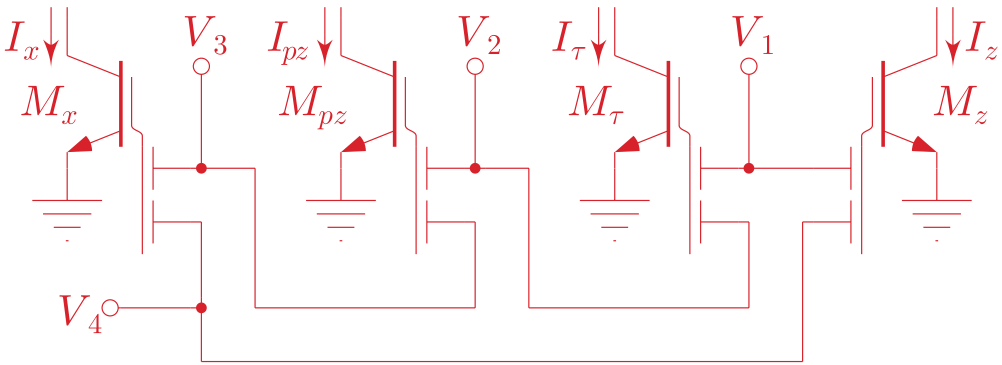

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad$ $I_y I_{py} = I_z I_\tau$

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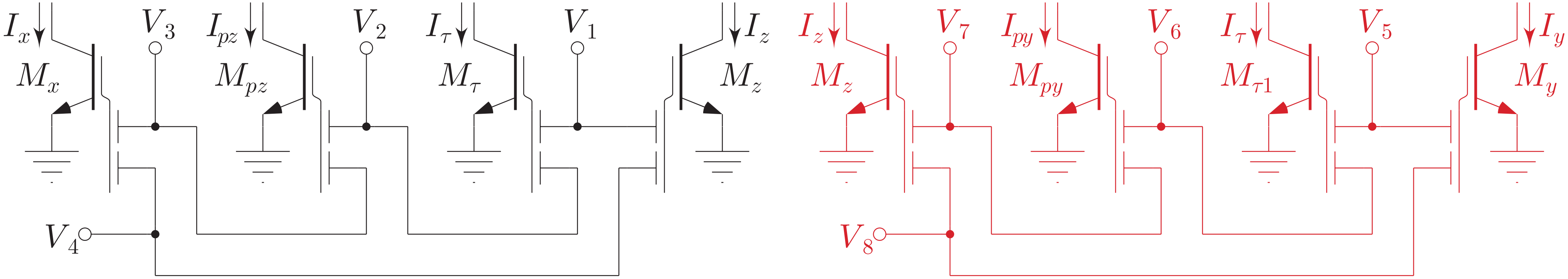

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad$ $I_y I_{py} = I_z I_\tau$ $\quad$ KCL: $I_{pz} + I_{cz} = I_w$

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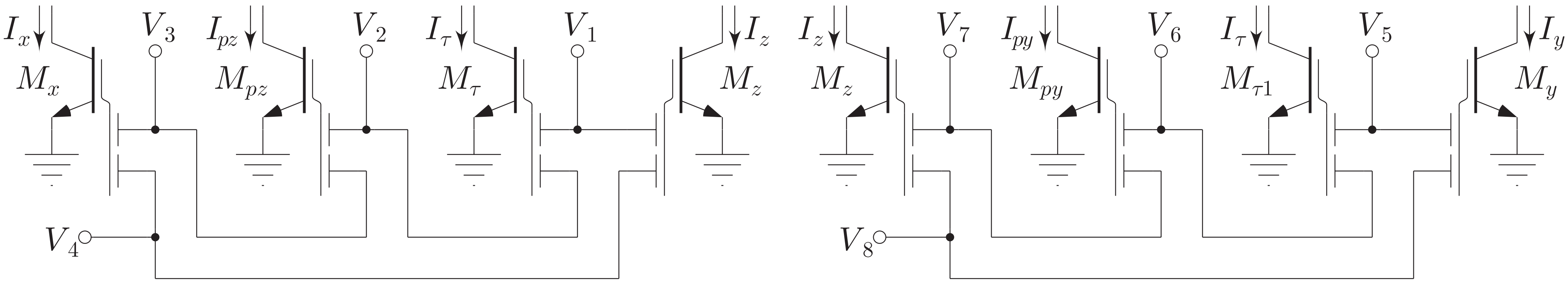

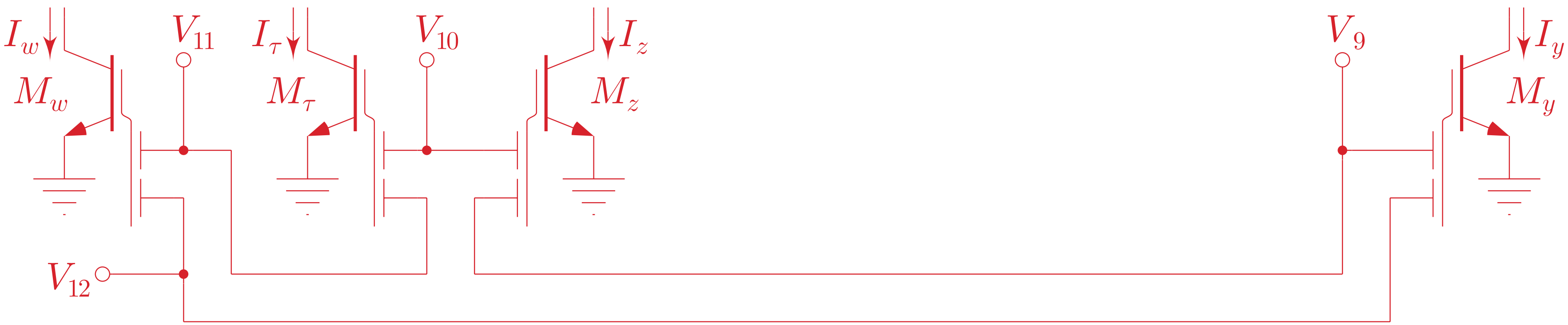

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau \qquad I_y I_{py} = I_z I_\tau$

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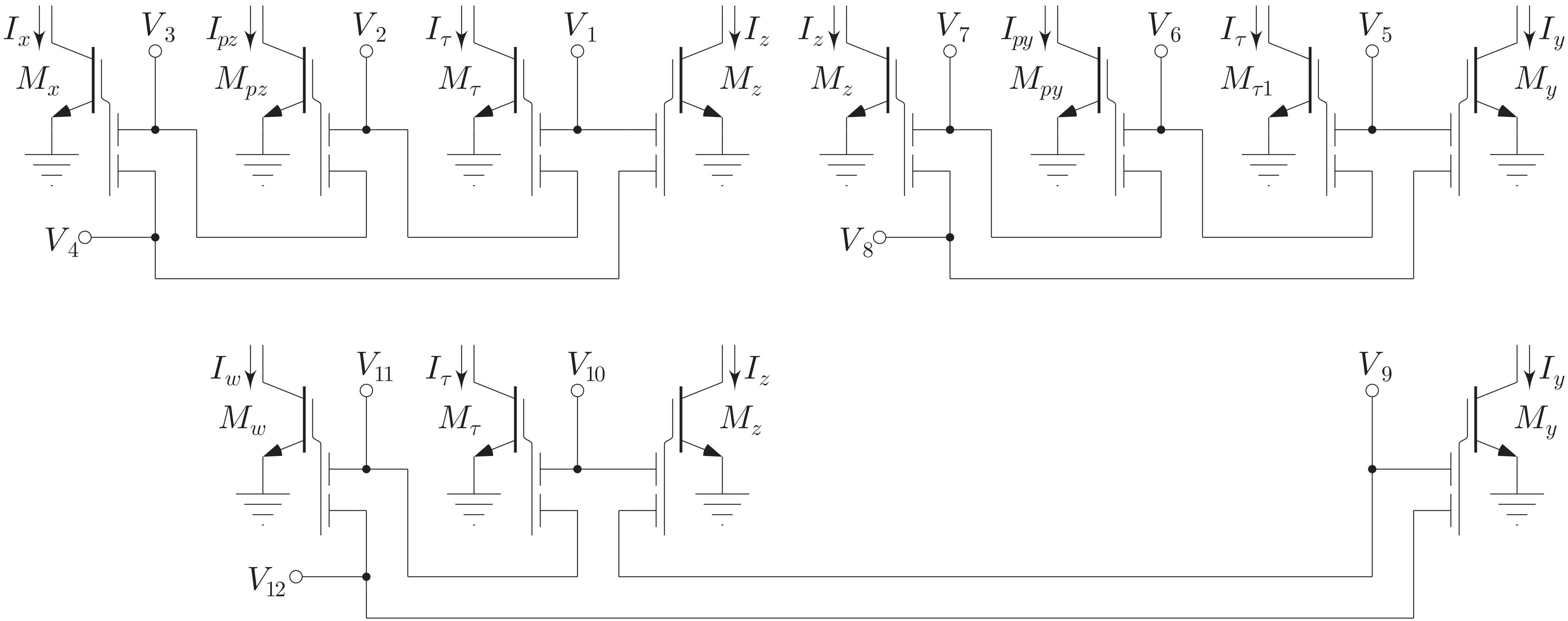

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TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

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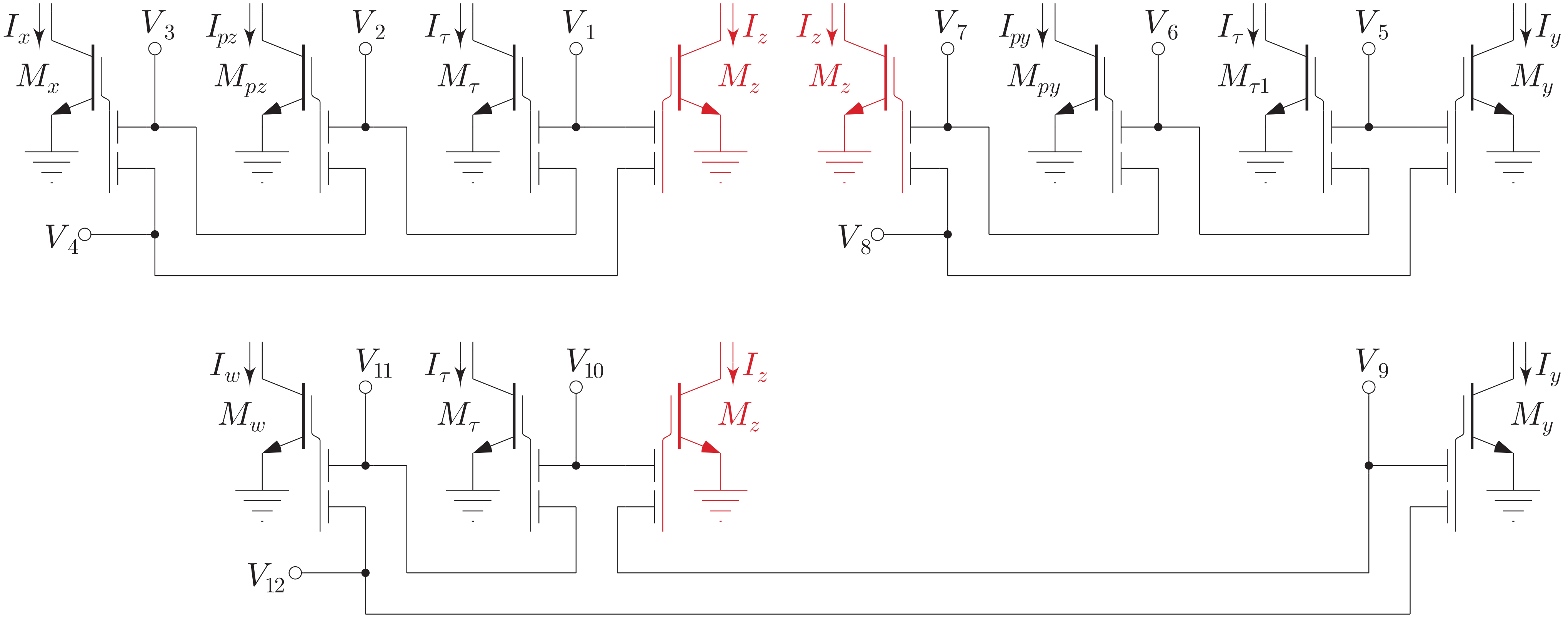

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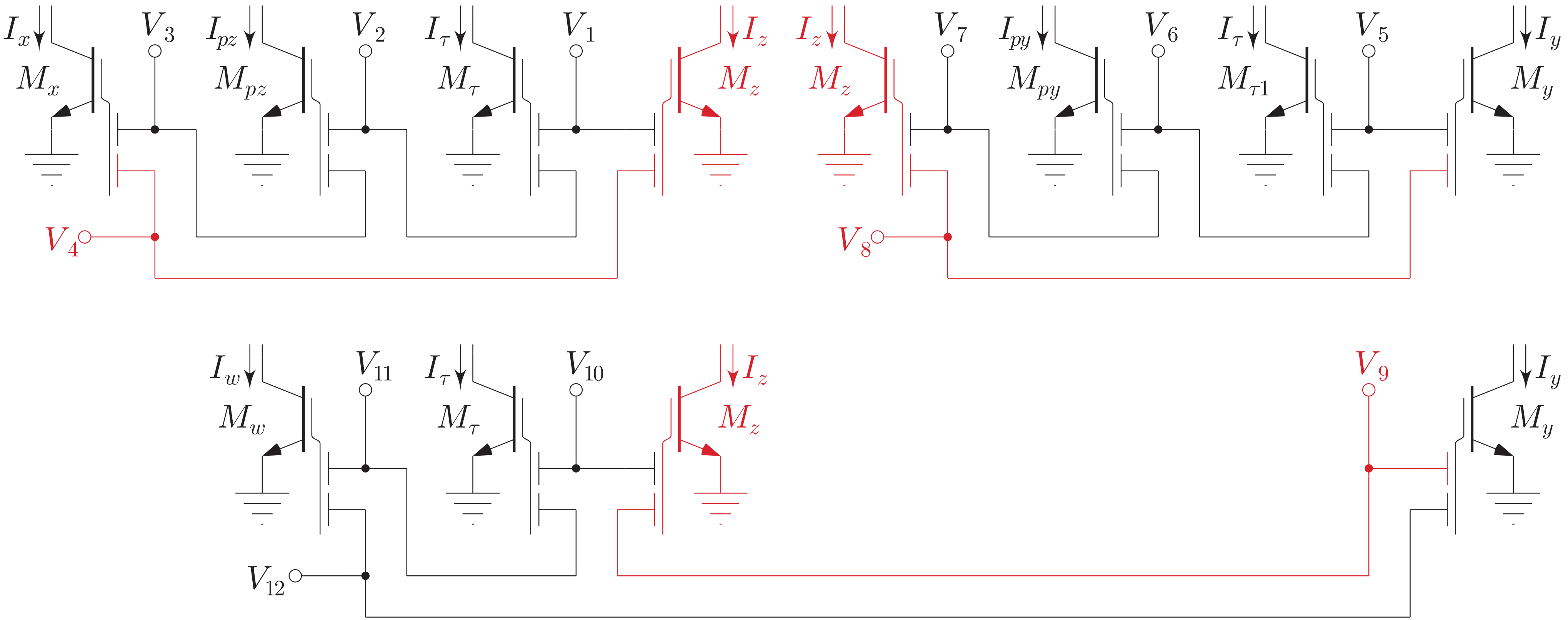

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

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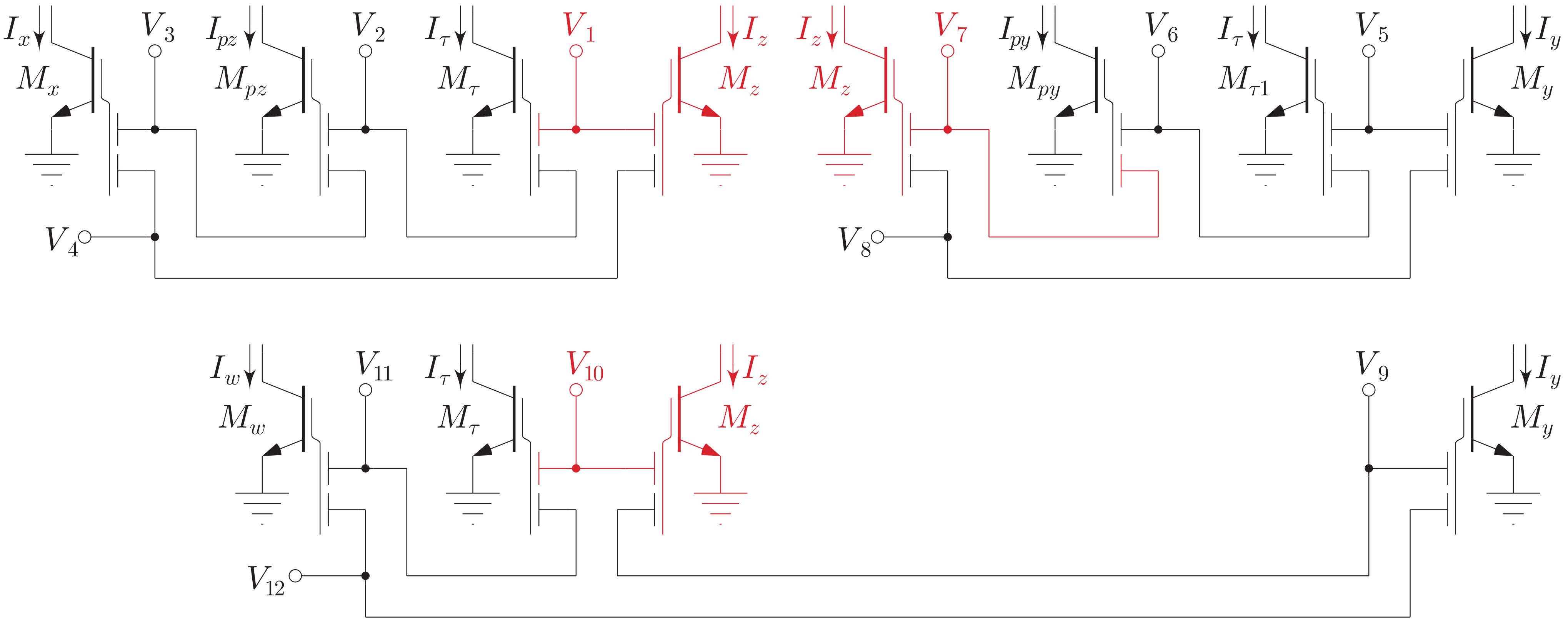

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau \qquad I_y I_{py} = I_z I_\tau$

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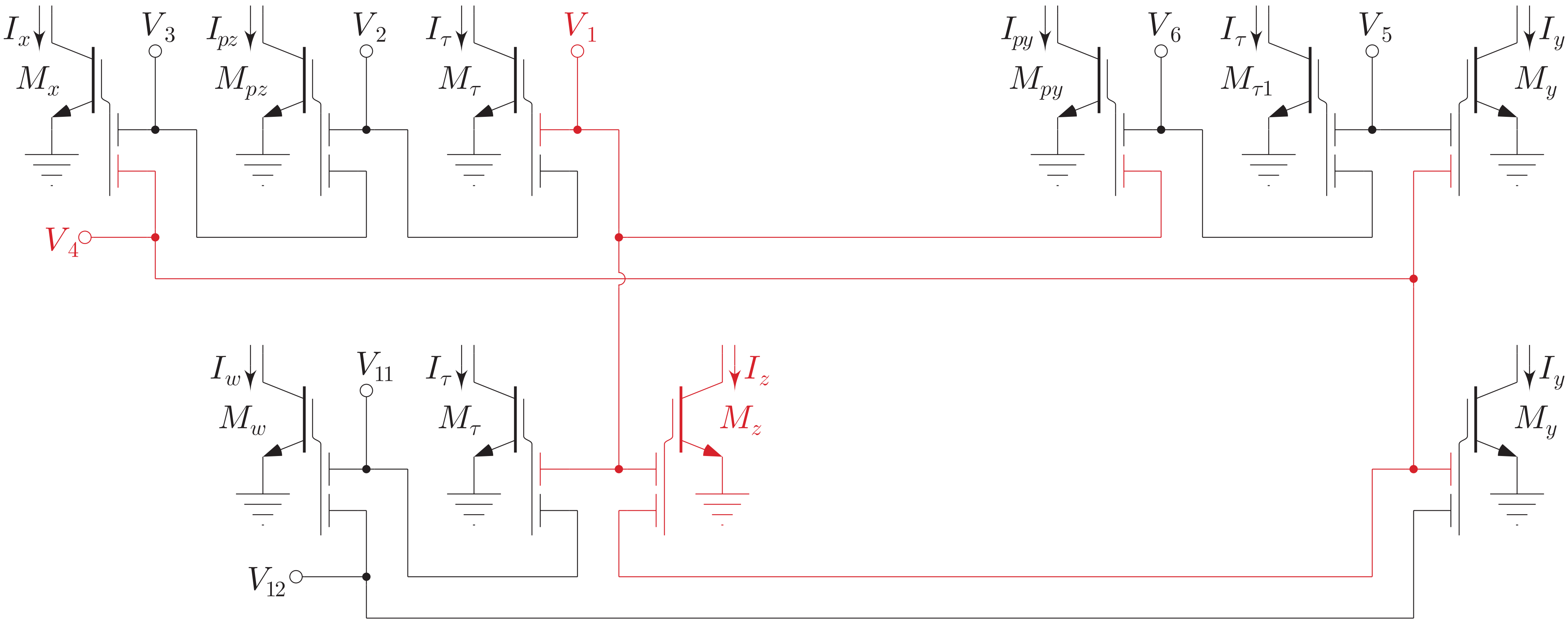

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad$ $I_y I_{py} = I_z I_\tau$

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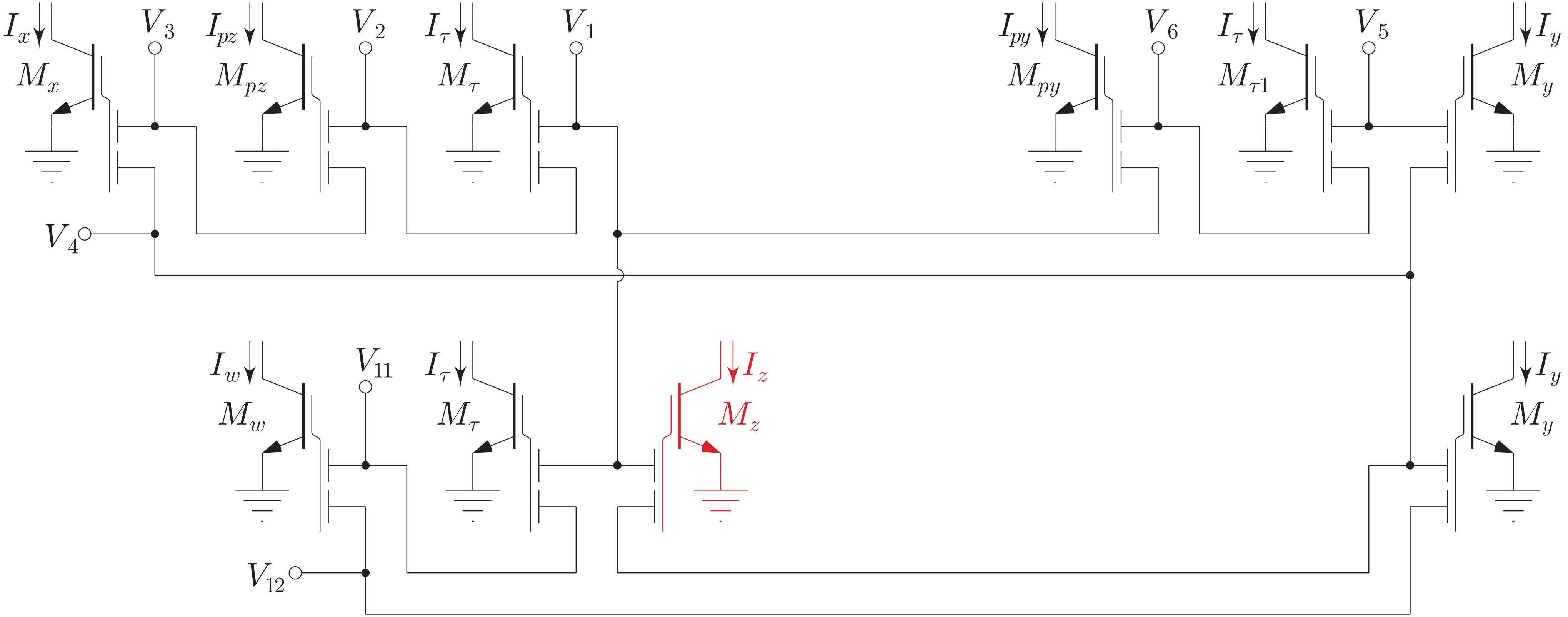

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Dynamic MITE Network Synthesis: Second-Order LPF

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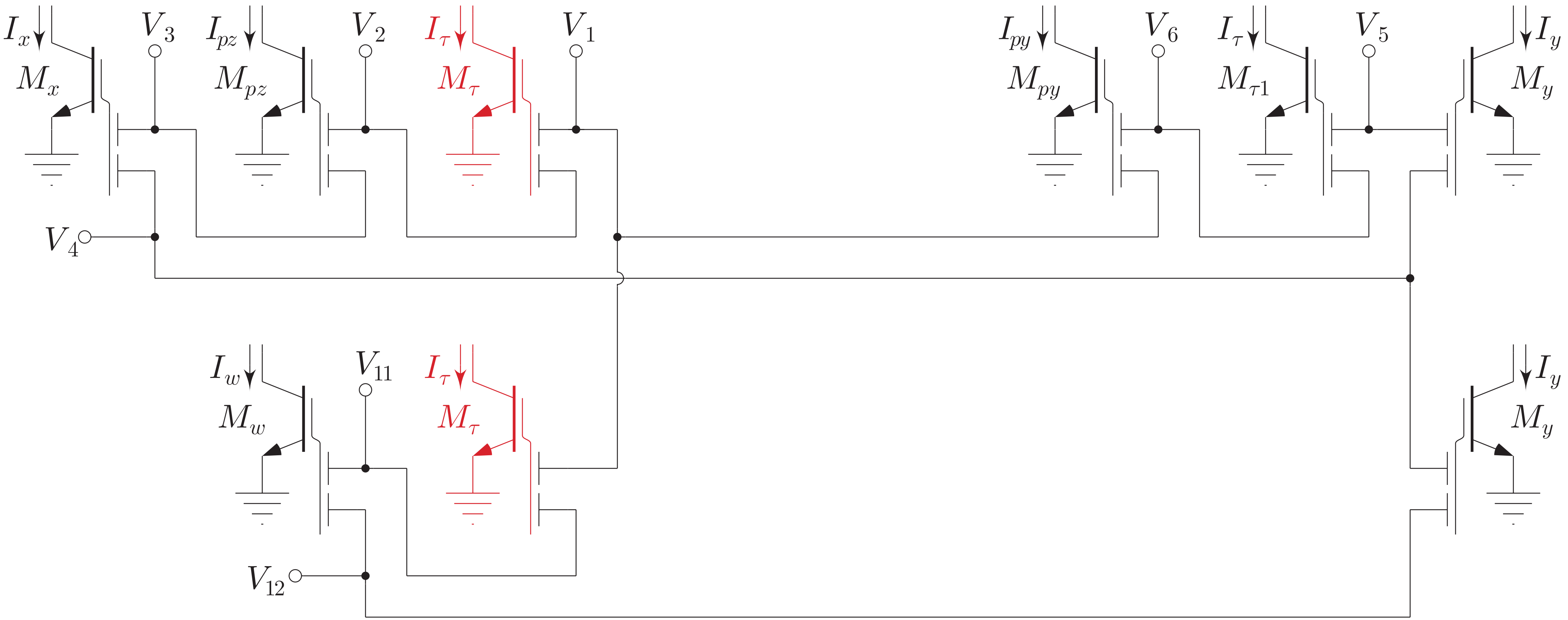

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Dynamic MITE Network Synthesis: Second-Order LPF

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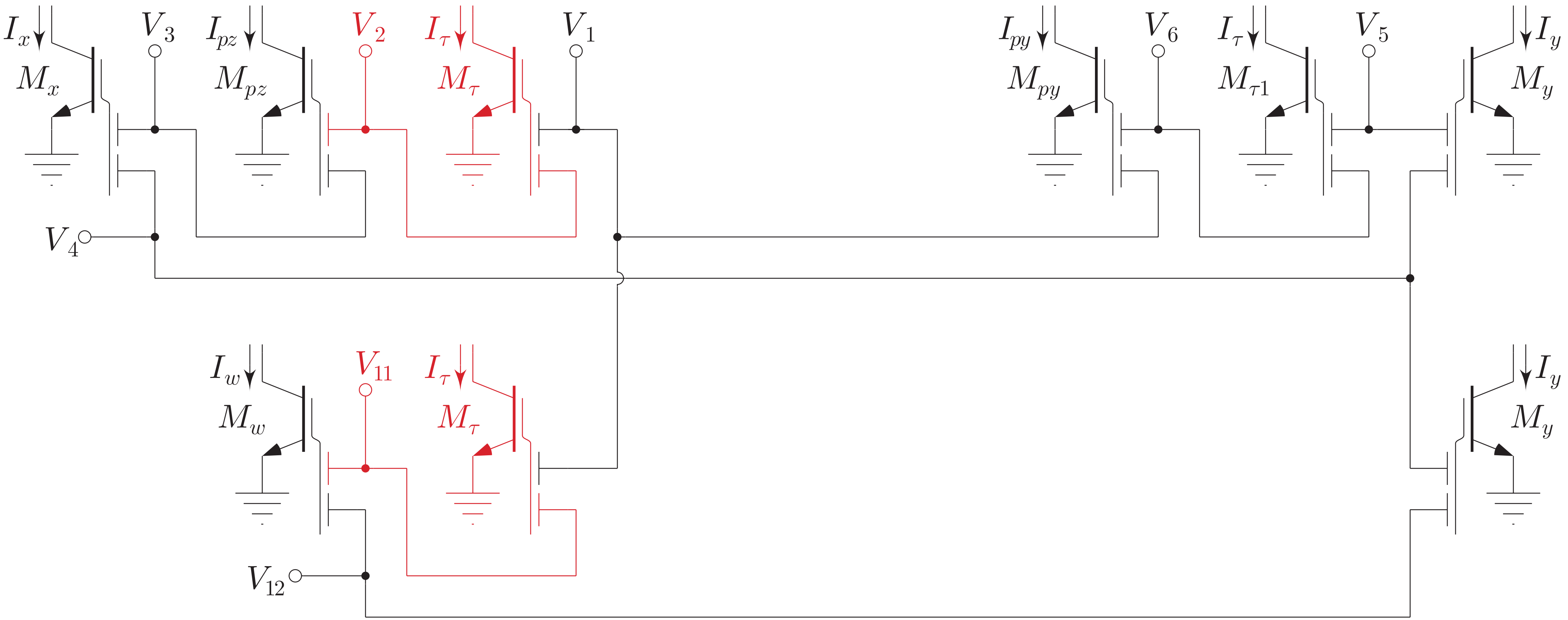

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau \qquad I_y I_{py} = I_z I_\tau$

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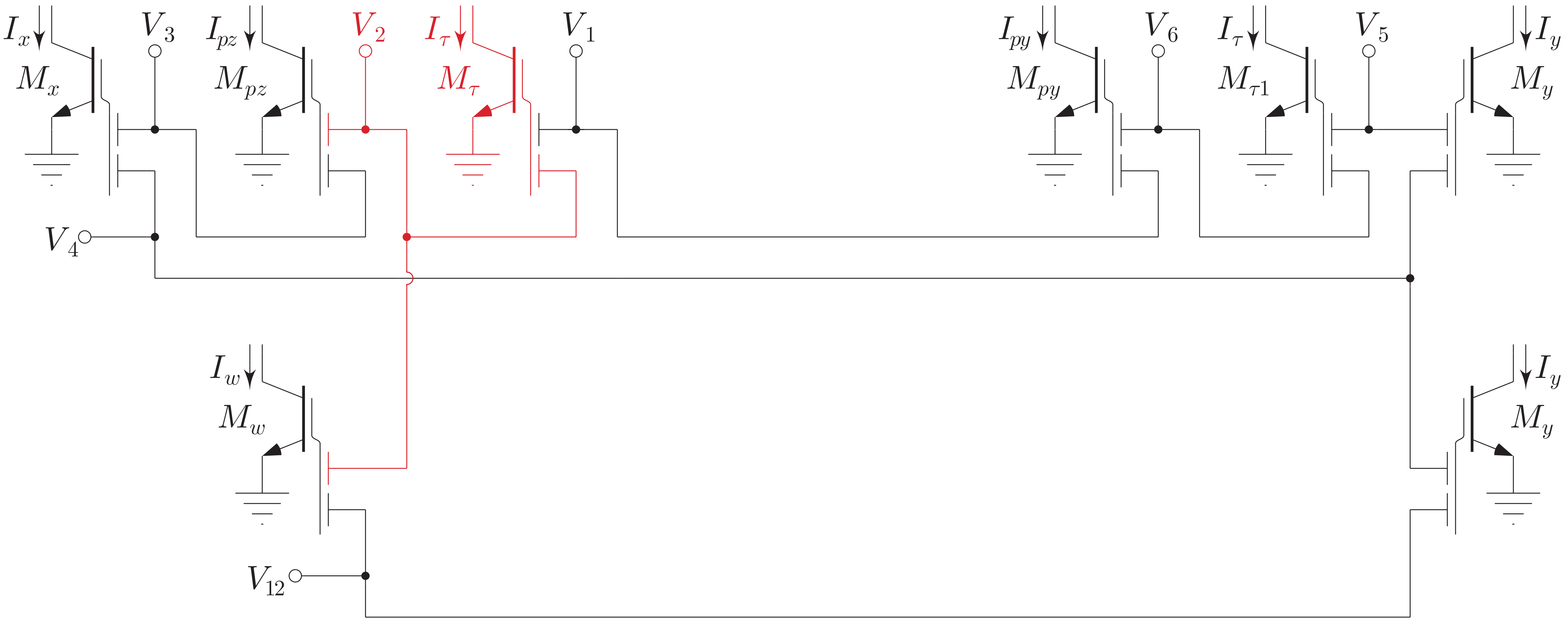

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$
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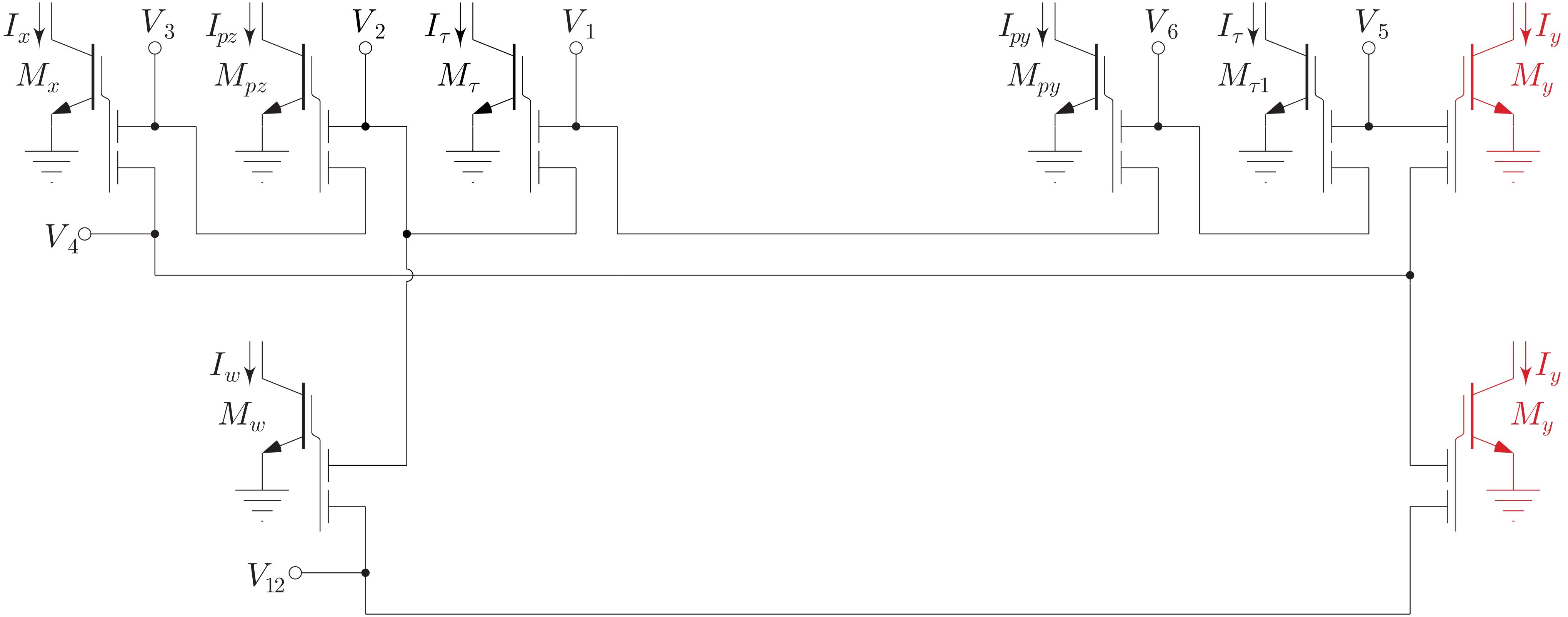

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

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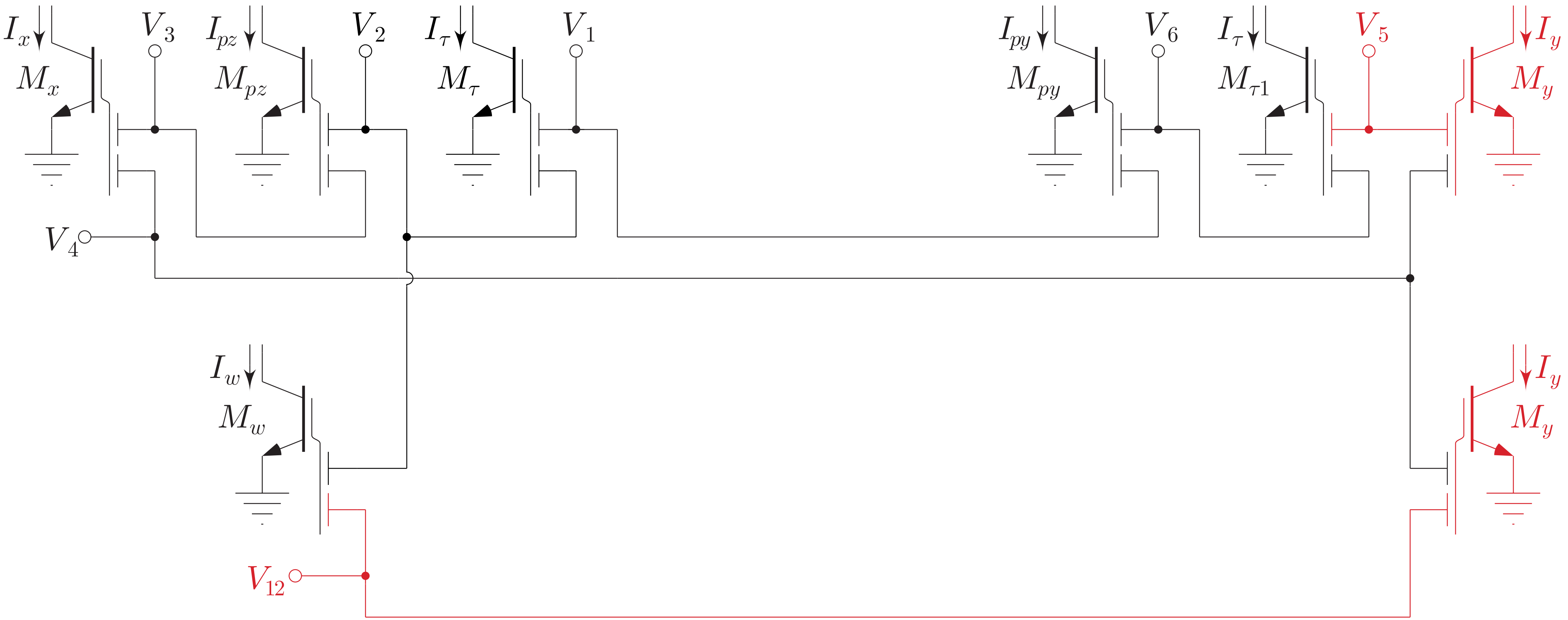

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$
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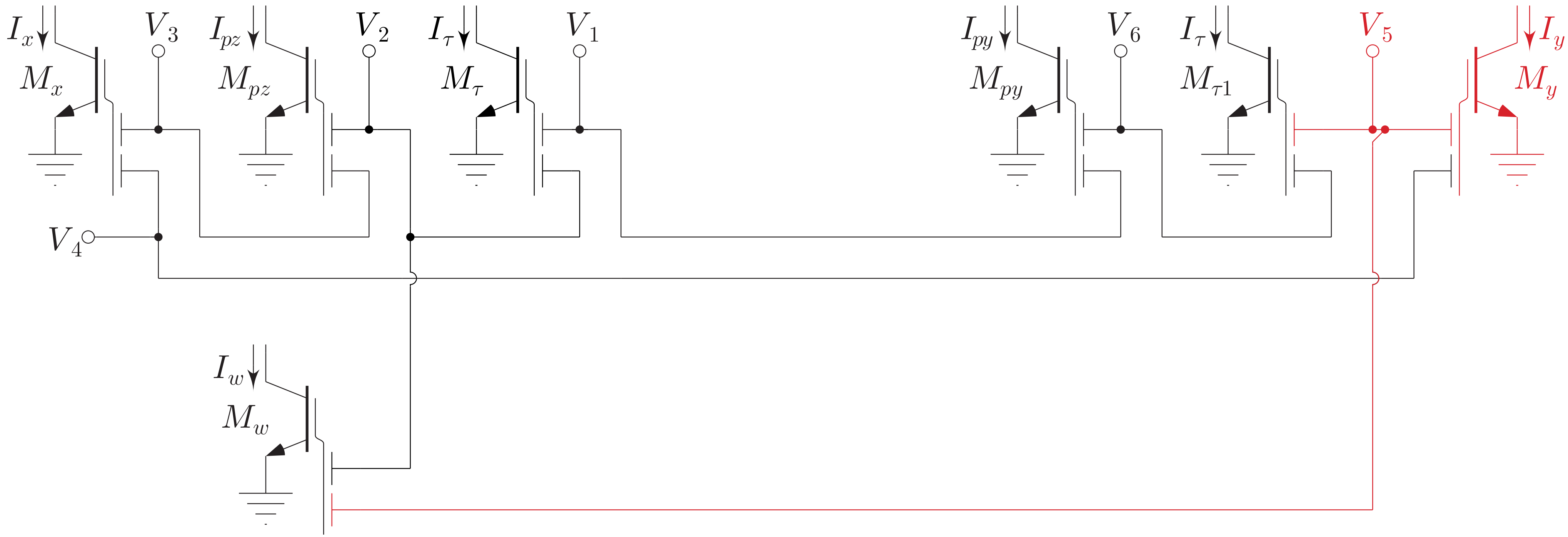

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $I_y I_{py} = I_z I_\tau$
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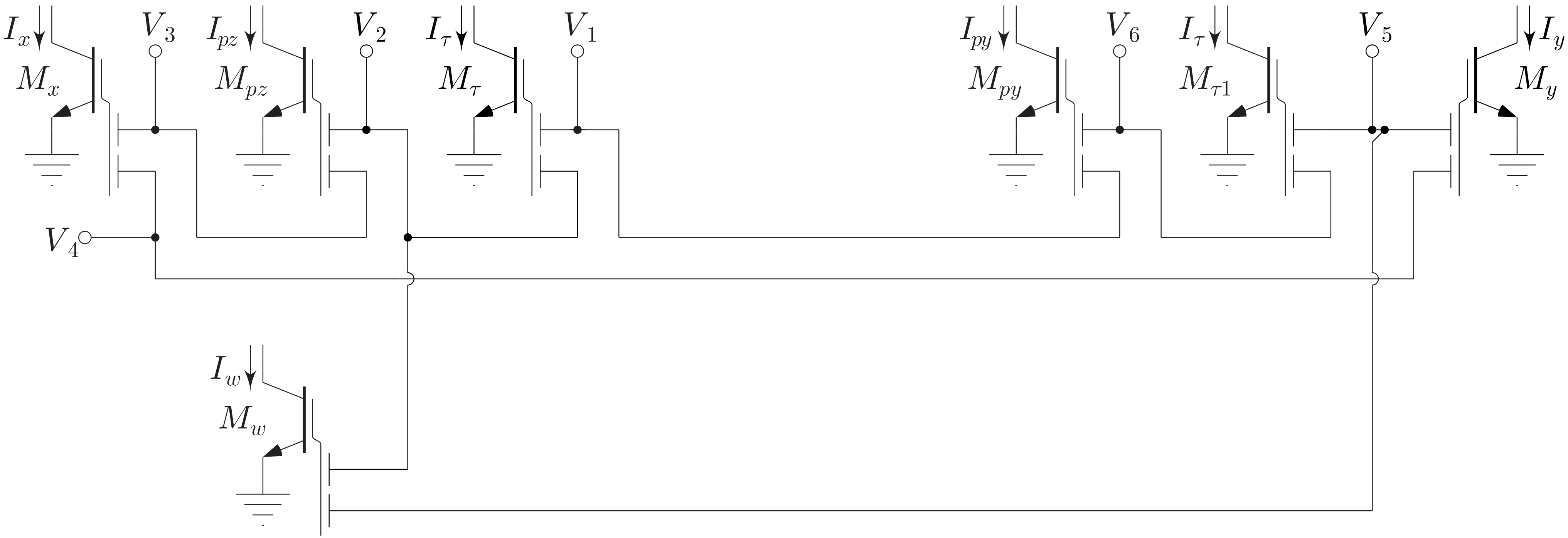

Dynamic MITE Network Synthesis: Second-Order LPF

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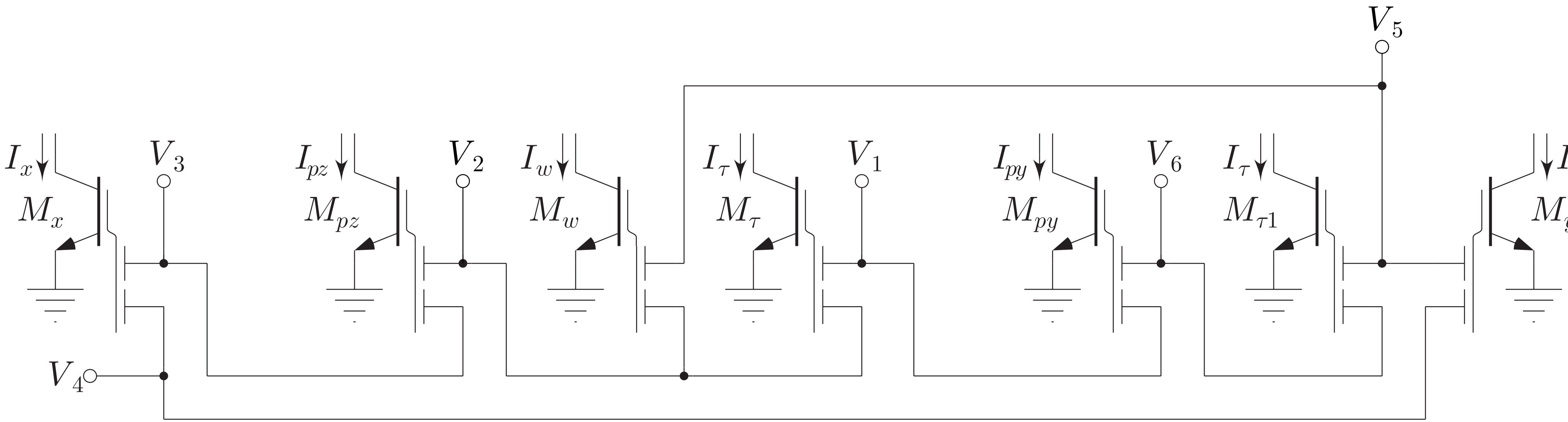

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau \qquad I_y I_{py} = I_z I_\tau$

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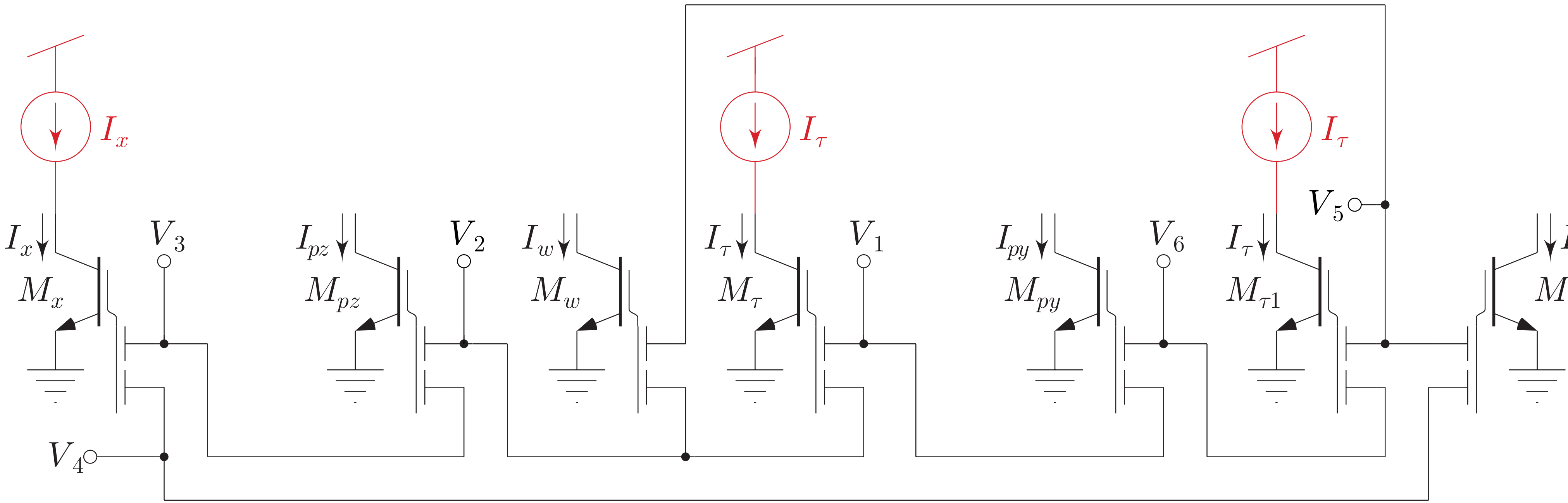

Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

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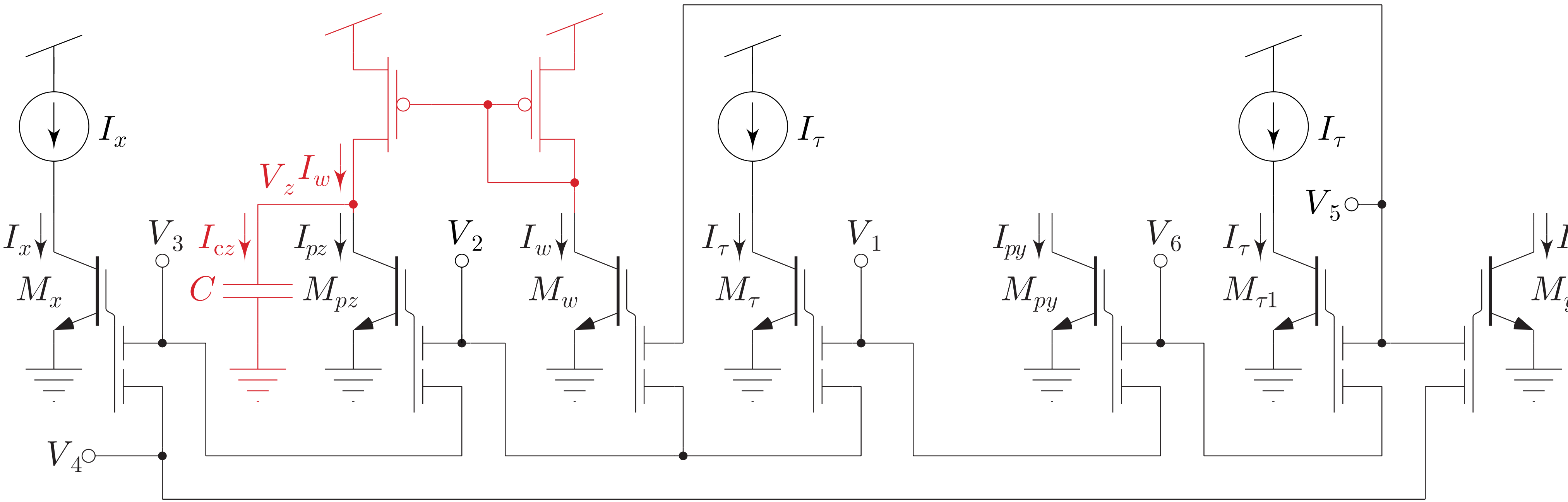

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad$ $I_y I_{py} = I_z I_\tau$

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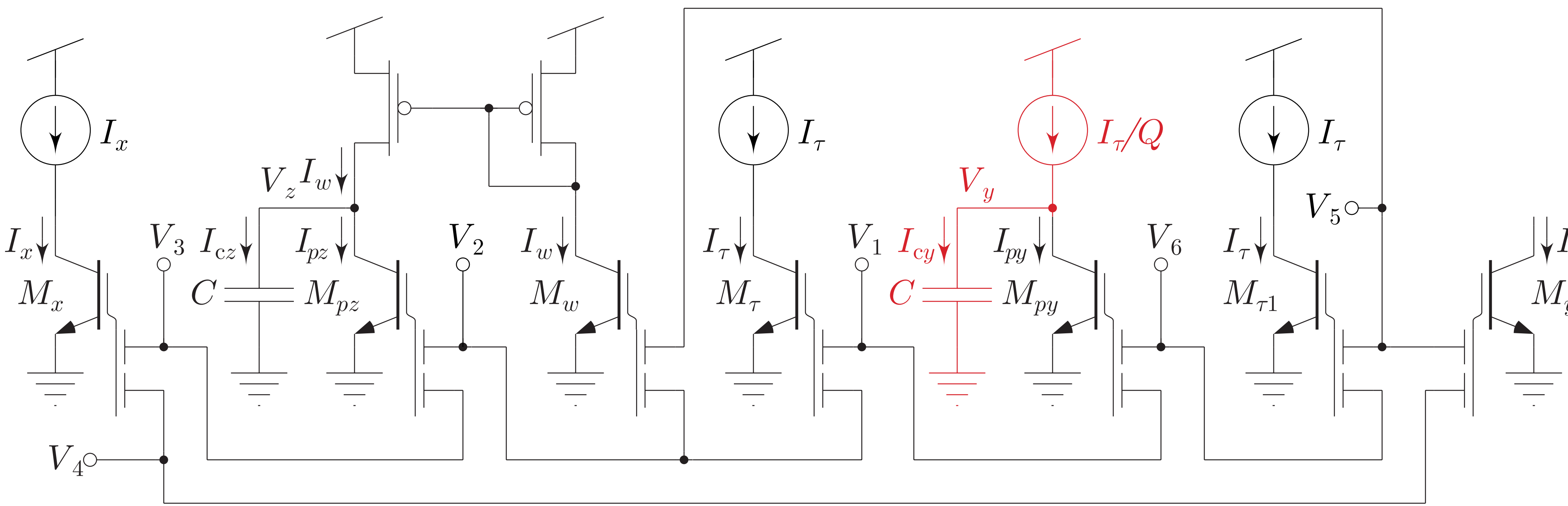

Dynamic MITE Network Synthesis: Second-Order LPF

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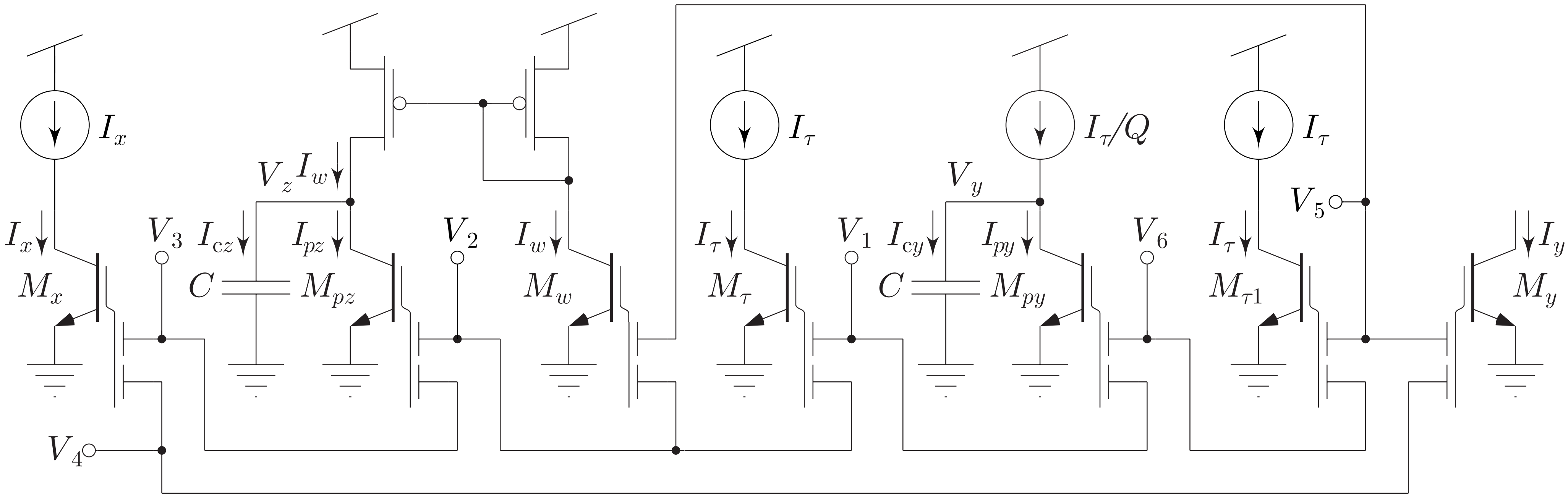

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad$ $I_y I_{py} = I_z I_\tau$

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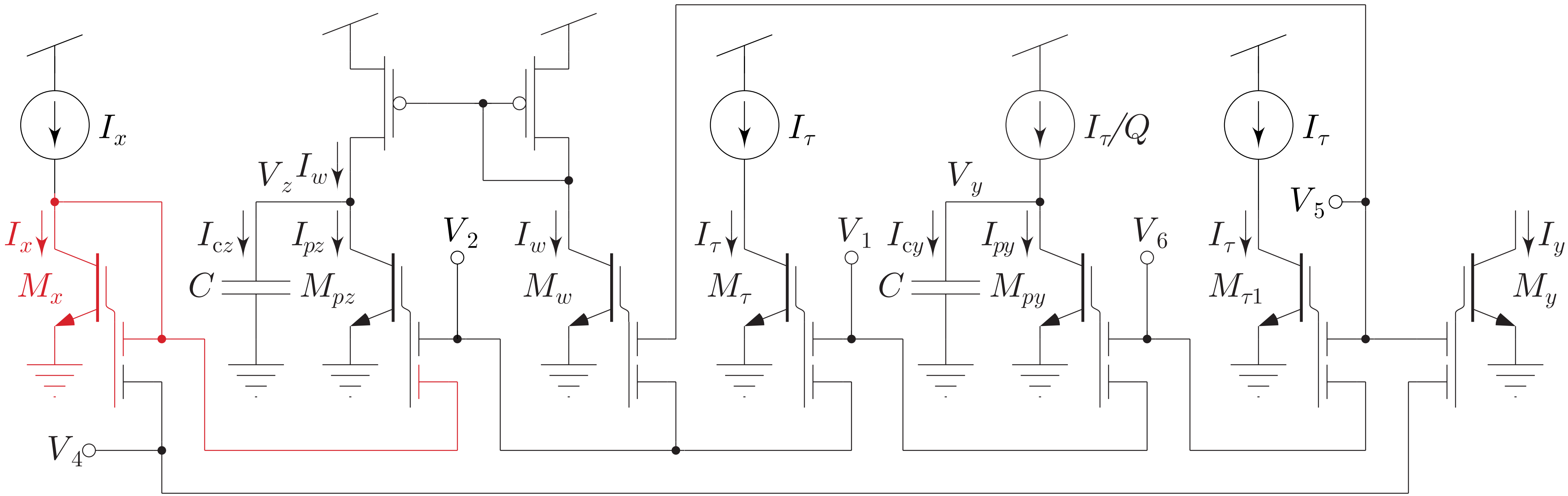

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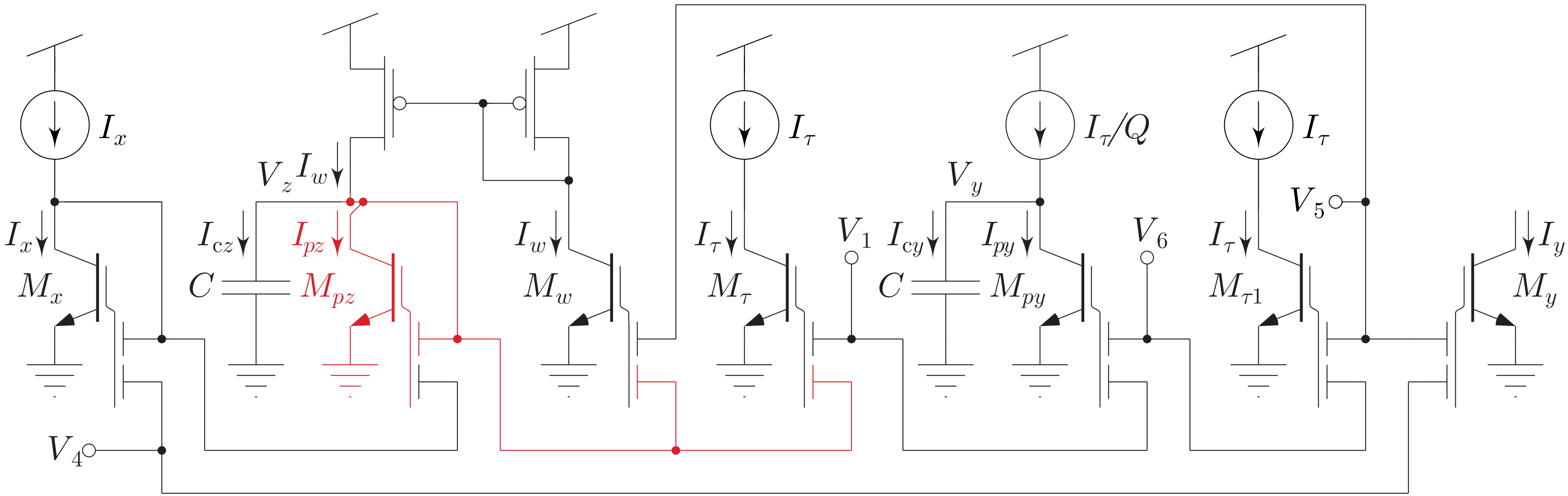

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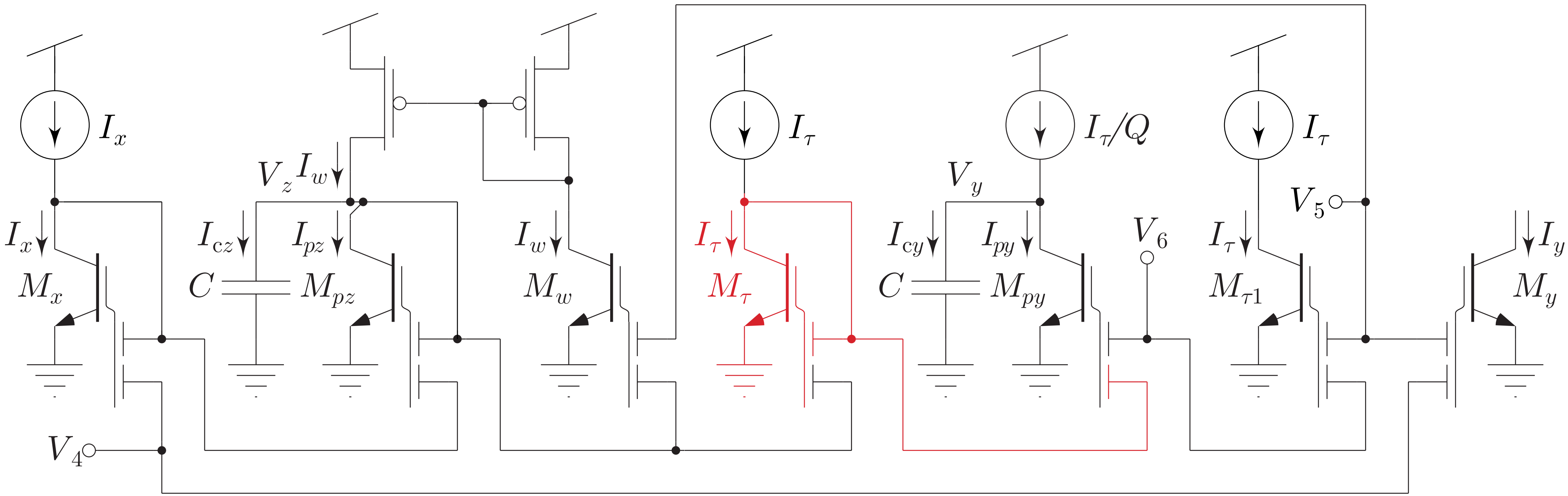

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Dynamic MITE Network Synthesis: Second-Order LPF

TLP: $I_z I_{pz} = I_x I_\tau$ $\quad I_y I_{py} = I_z I_\tau$

$I_z I_w = I_y I_\tau$

KCL: $I_{pz} + I_{cz} = I_w$

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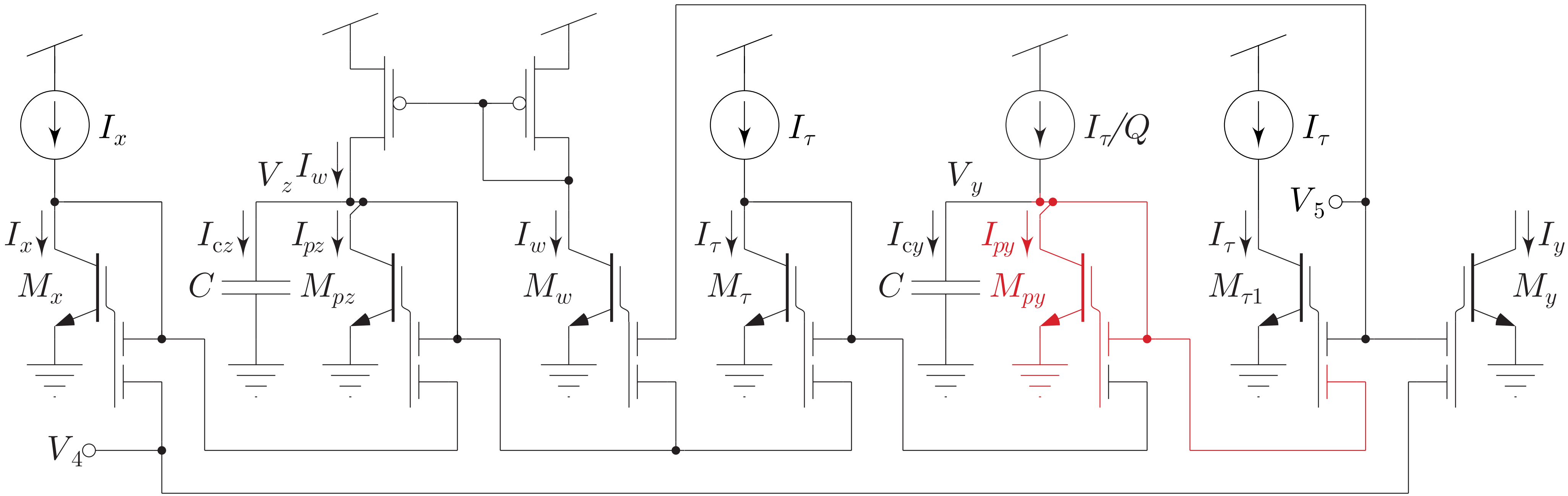

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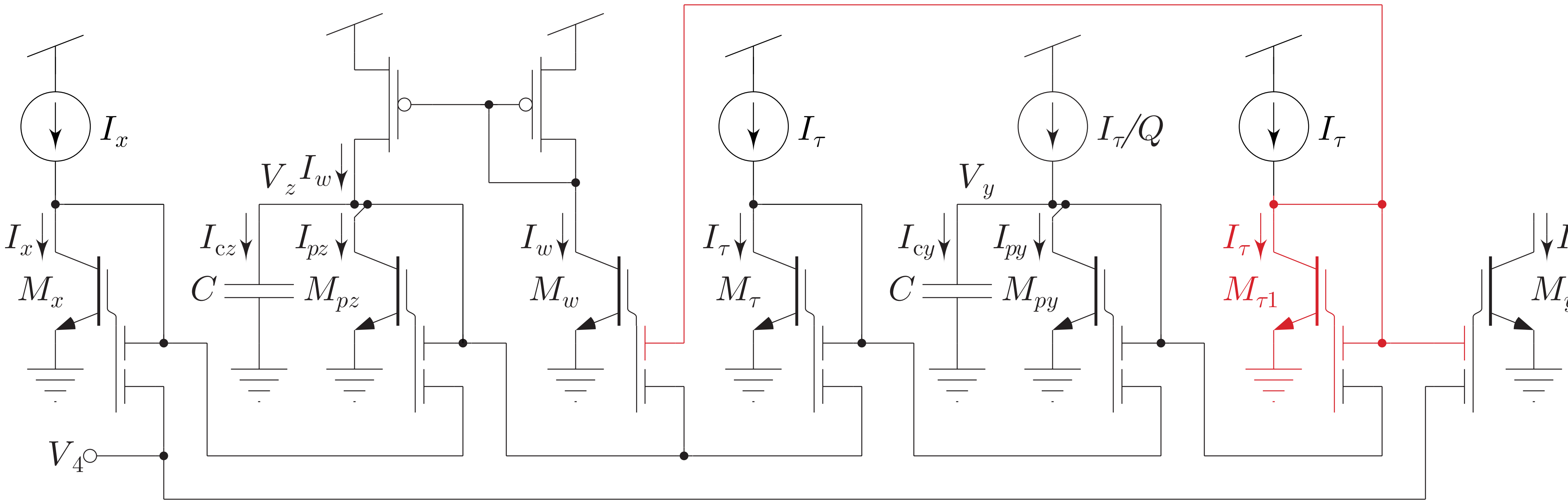

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Dynamic MITE Network Synthesis: Second-Order LPF

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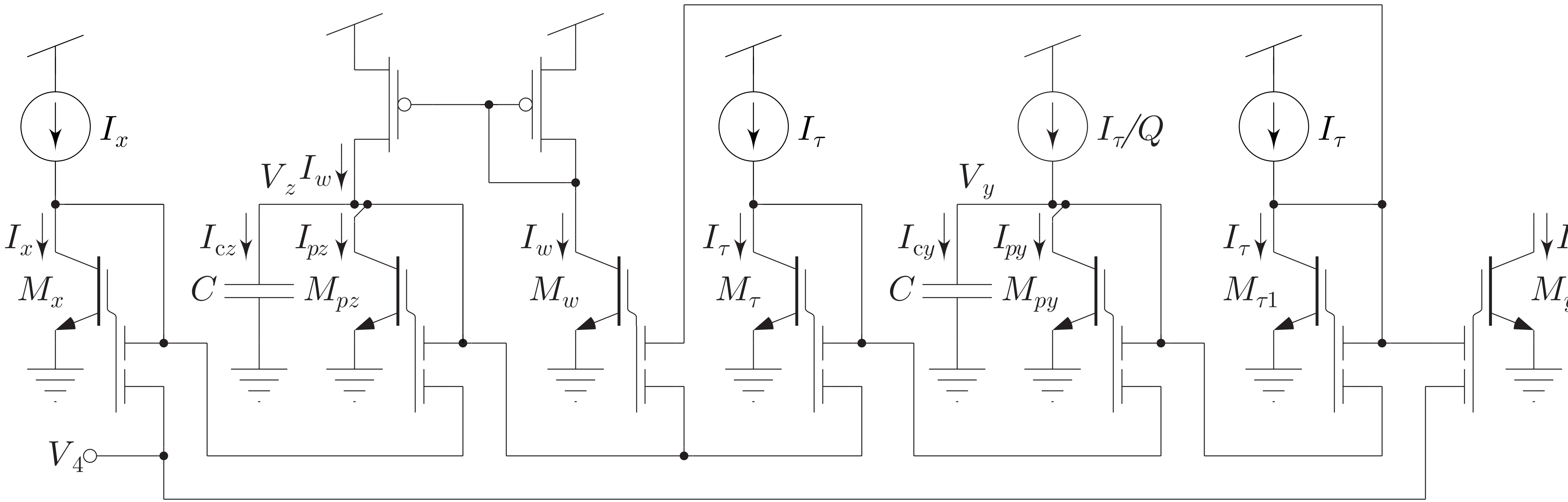

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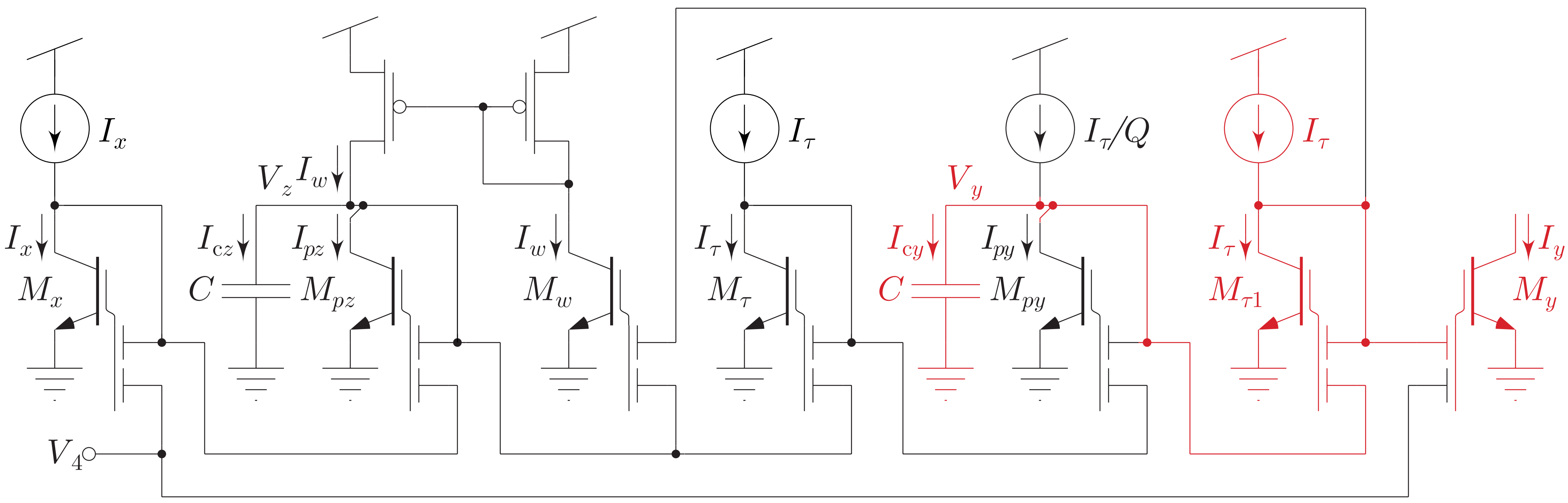

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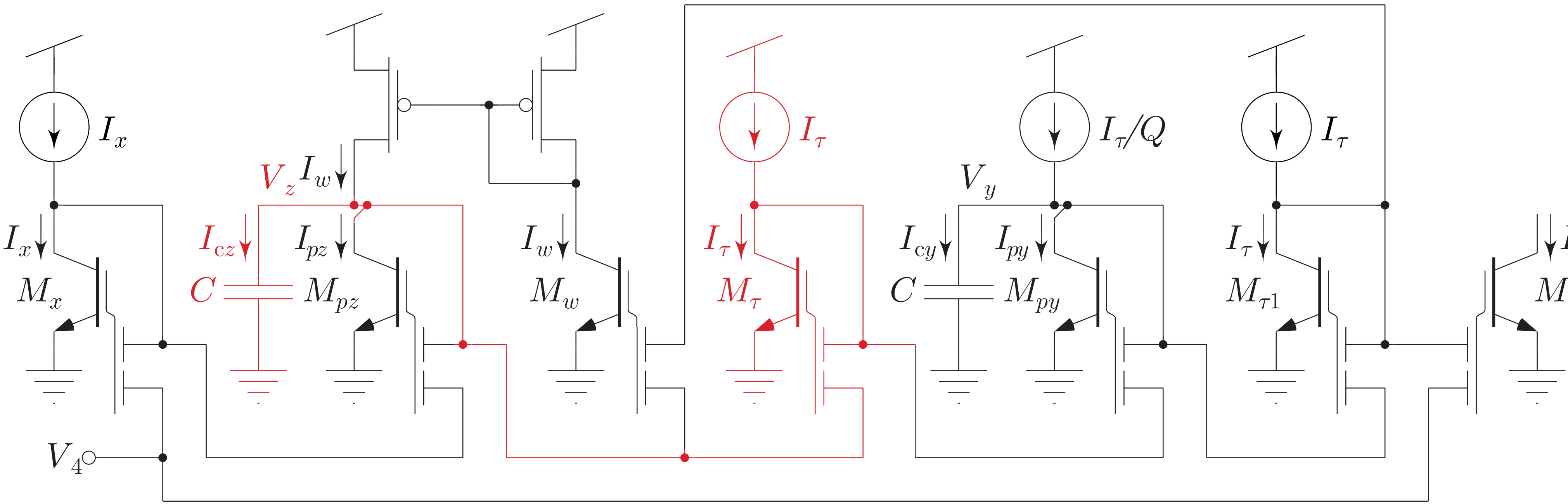

Dynamic MITE Network Synthesis: RMS-to-DC Converter

Synthesize an RMS-to-DC converter described by

$$x = w^2, \quad \tau \frac{dy}{dt} + y = x, \quad \text{and} \quad z = \sqrt{y}.$$

Dynamic MITE Network Synthesis: RMS-to-DC Converter

Synthesize an RMS-to-DC converter described by

$$x = w^2, \quad \tau\frac{dy}{dt} + y = x, \quad \text{and} \quad z = \sqrt{y}.$$

We can eliminate x and y from the system description by substituting

$$x = w^2, \quad y = z^2, \quad \text{and} \quad \frac{dy}{dt} = 2z\frac{dz}{dt}$$

into the linear ODE describing the low-pass filter, obtaining a first-order nonlinear ODE describing the system given by

$$2\tau z\frac{dz}{dt} + z^2 = w^2.$$

Dynamic MITE Network Synthesis: RMS-to-DC Converter

The input signal, w, can be positive or negative. To remedy this situation, we can offset w by defining $u \equiv w + v$, such that $u > 0$ and $v > 0$. Substituting $w = u - v$ into the nonlinear ODE, we obtain

$$2\tau z \frac{dz}{dt} + z^2 = u^2 - 2uv + v^2.$$

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We represent each signal as a ratio of a signal current to the unit current:

$$u \equiv \frac{I_u}{I_1}, \quad v \equiv \frac{I_v}{I_1}, \quad \text{and} \quad z \equiv \frac{I_z}{I_1}.$$

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Substituting these into the nonlinear ODE, we obtain

$$2\tau \frac{I_z}{I_1} \cdot \frac{d}{dt}\left(\frac{I_z}{I_1}\right) + \left(\frac{I_z}{I_1}\right)^2 = \left(\frac{I_u}{I_1}\right)^2 - 2 \cdot \frac{I_u}{I_1} \cdot \frac{I_v}{I_1} + \left(\frac{I_v}{I_1}\right)^2$$

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Dynamic MITE Network Synthesis: RMS-to-DC Converter

To implement the time derivative, we introduce a log-compressed voltage state variable, V_z. Using the chain rule, we can express the preceding equation as

$$2\tau I_z \frac{\partial I_z}{\partial V_z} \cdot \frac{dV_z}{dt} + I_z^2 = I_u^2 - 2I_u I_v + I_v^2$$

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$$\Longrightarrow -\frac{2w\tau}{U_\mathrm{T}} \cdot \frac{dV_z}{dt} + 1 = \frac{I_u^2}{I_z^2} - \frac{2I_u I_v}{I_z^2} + \frac{I_v^2}{I_z^2}$$

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$$\Longrightarrow -\frac{I_c}{I_\tau} + 1 = \frac{I_u^2}{I_z^2} - \frac{2I_uI_v}{I_z^2} + \frac{I_v^2}{I_z^2}$$

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$$\implies -\frac{2w\tau}{U_\mathrm{T}} \cdot \frac{dV_z}{dt} + 1 = \frac{I_u^2}{I_z^2} - \frac{2I_u I_v}{I_z^2} + \frac{I_v^2}{I_z^2} \implies -\underbrace{\frac{2w\tau}{CU_\mathrm{T}}}_{1/I_\tau} \cdot \underbrace{C\frac{dV_z}{dt}}_{I_c} + 1 = \frac{I_u^2}{I_z^2} - \frac{2I_u I_v}{I_z^2} + \frac{I_v^2}{I_z^2}$$

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Dynamic MITE Network Synthesis: RMS-to-DC Converter

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To implement the time derivative, we introduce a log-compressed voltage state variable, V_z. Using the chain rule, we can express the preceding equation as

$$2\tau I_z \frac{\partial I_z}{\partial V_z} \cdot \frac{dV_z}{dt} + I_z^2 = I_u^2 - 2I_u I_v + I_v^2 \implies 2\tau I_z \left(-\frac{w}{U_\mathrm{T}} I_z \right) \frac{dV_z}{dt} + I_z^2 = I_u^2 - 2I_u I_v + I_v^2$$

$$\implies -\frac{2w\tau}{U_\mathrm{T}} \cdot \frac{dV_z}{dt} + 1 = \frac{I_u^2}{I_z^2} - \frac{2I_u I_v}{I_z^2} + \frac{I_v^2}{I_z^2} \implies -\underbrace{\frac{2w\tau}{CU_\mathrm{T}}}_{1/I_\tau} \cdot \underbrace{C\frac{dV_z}{dt}}_{I_c} + 1 = \frac{I_u^2}{I_z^2} - \frac{2I_u I_v}{I_z^2} + \frac{I_v^2}{I_z^2}$$

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Dynamic MITE Network Synthesis: RMS-to-DC Converter

TLP: $I_p I_z^2 = I_\tau I_u^2$ $\quad$ $I_r I_z^2 = I_\tau I_v^2$ $\quad$ KCL: $I_p + I_r + I_c = I_\tau + I_q$

$I_q I_z^2 = I_\tau I_u I_{2v}$

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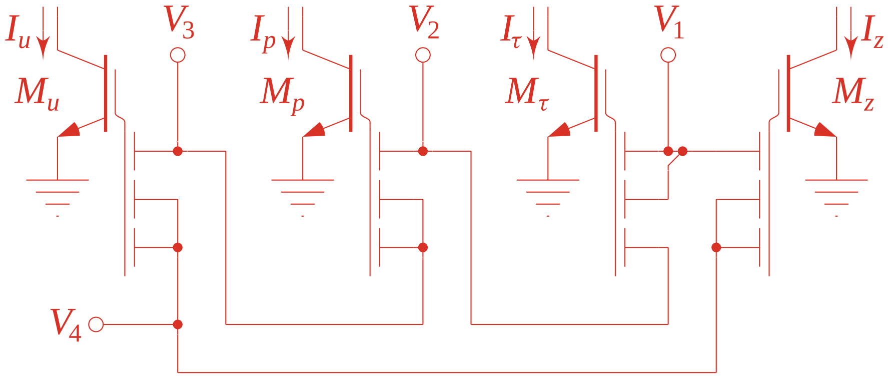

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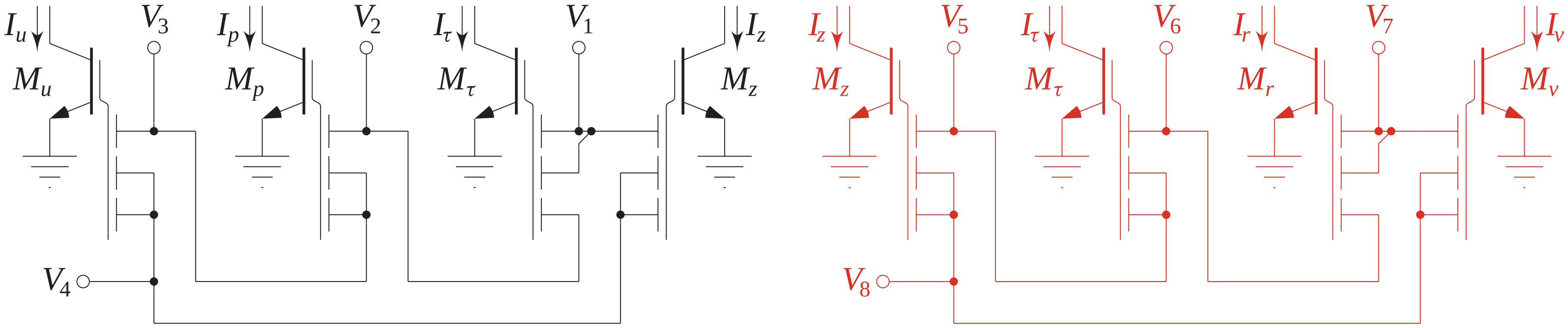

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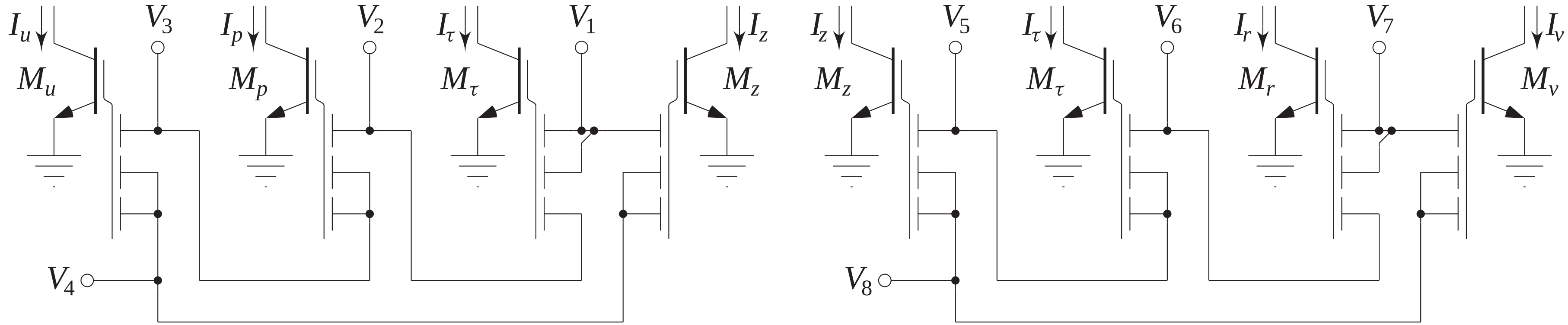

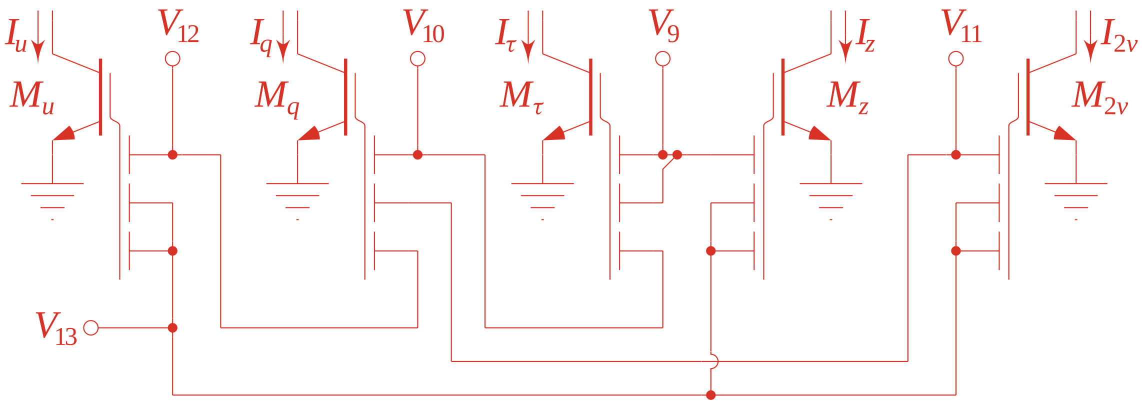

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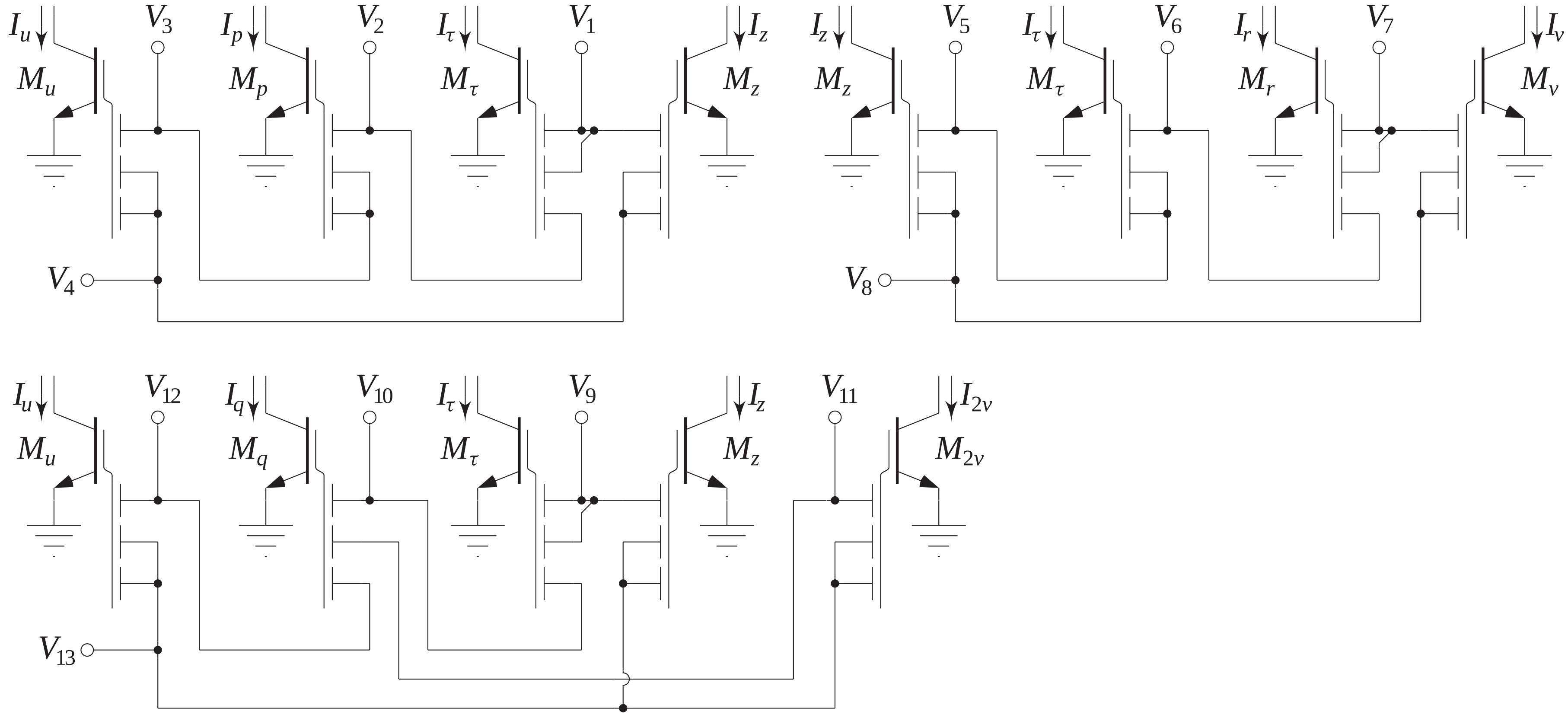

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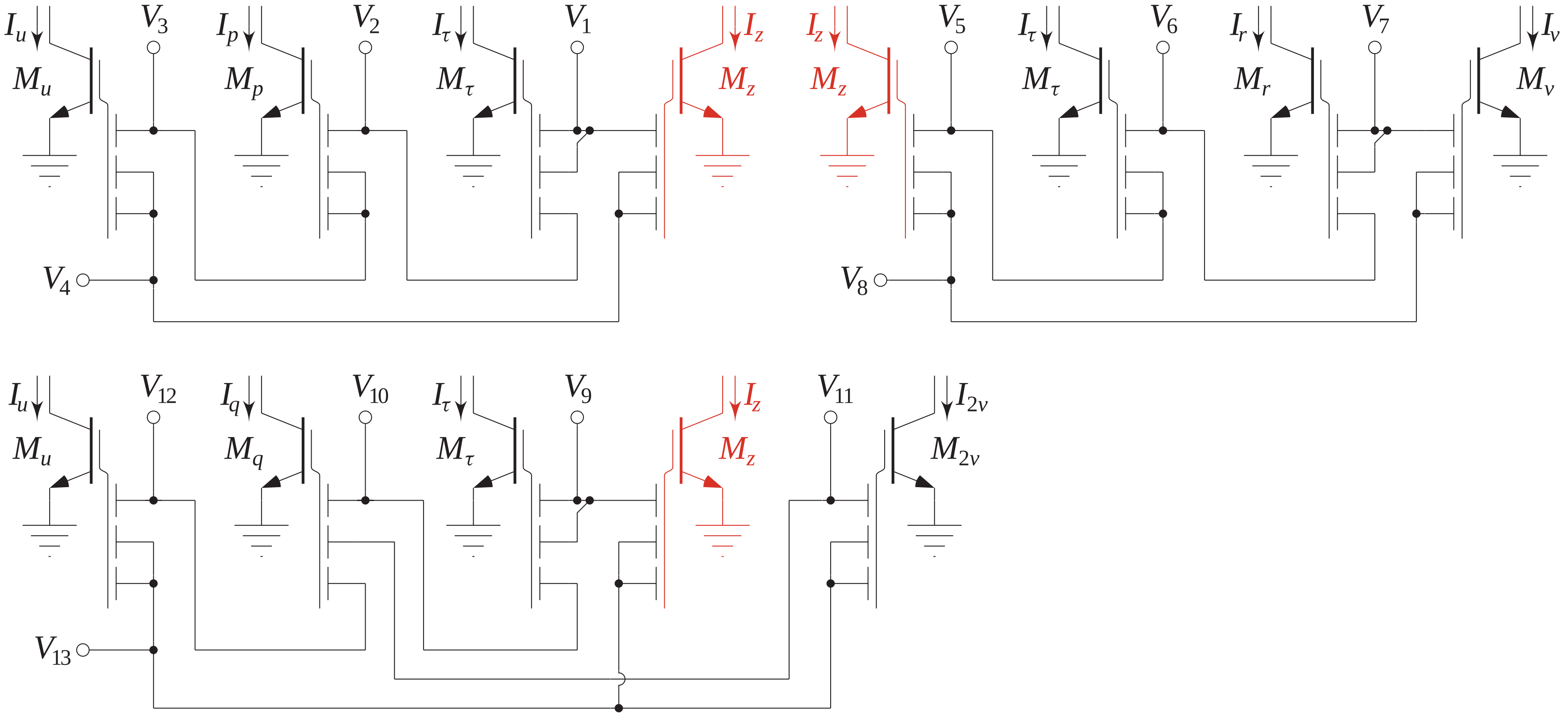

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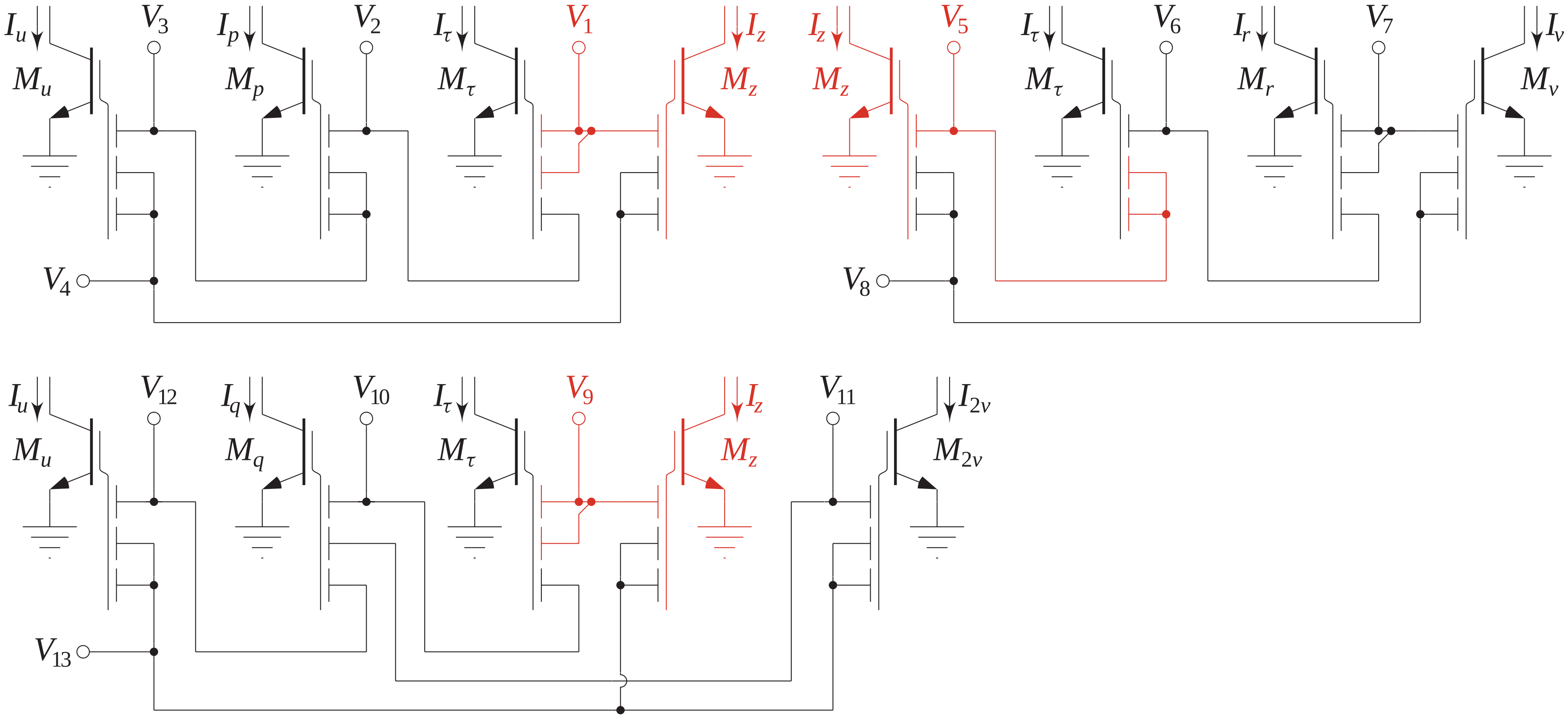

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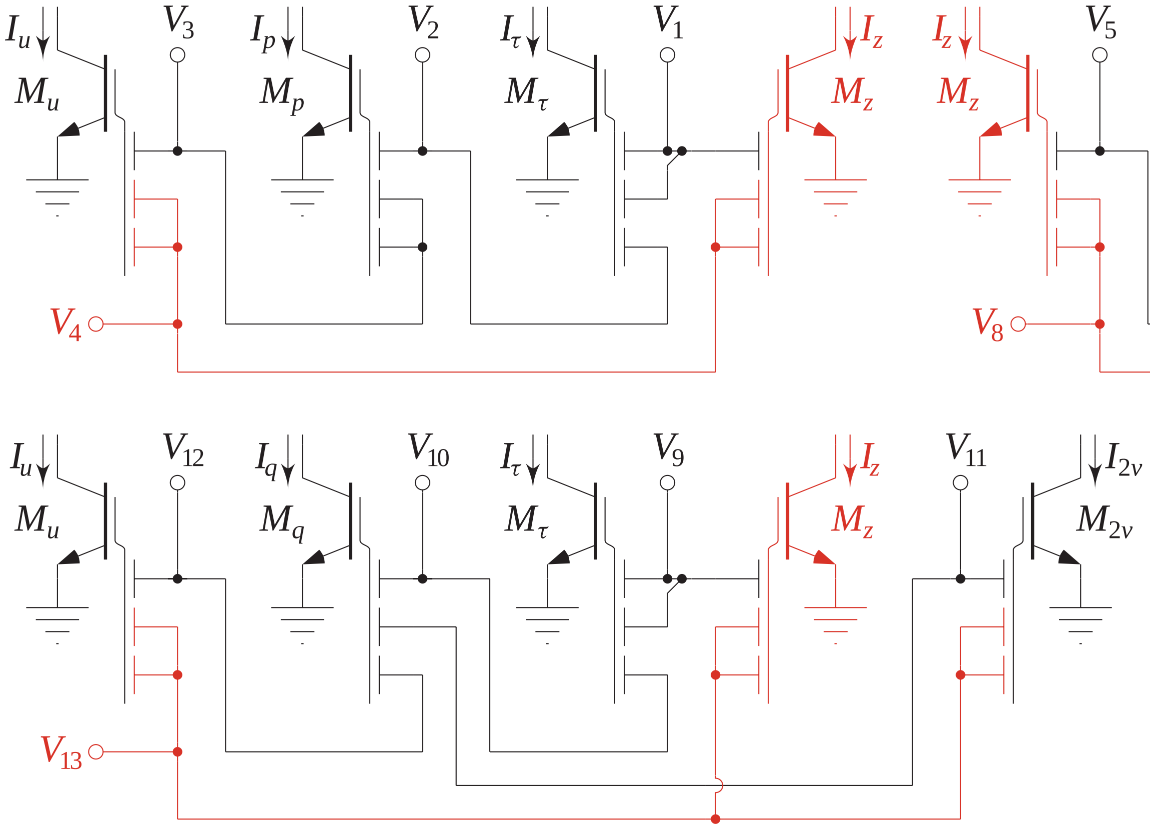

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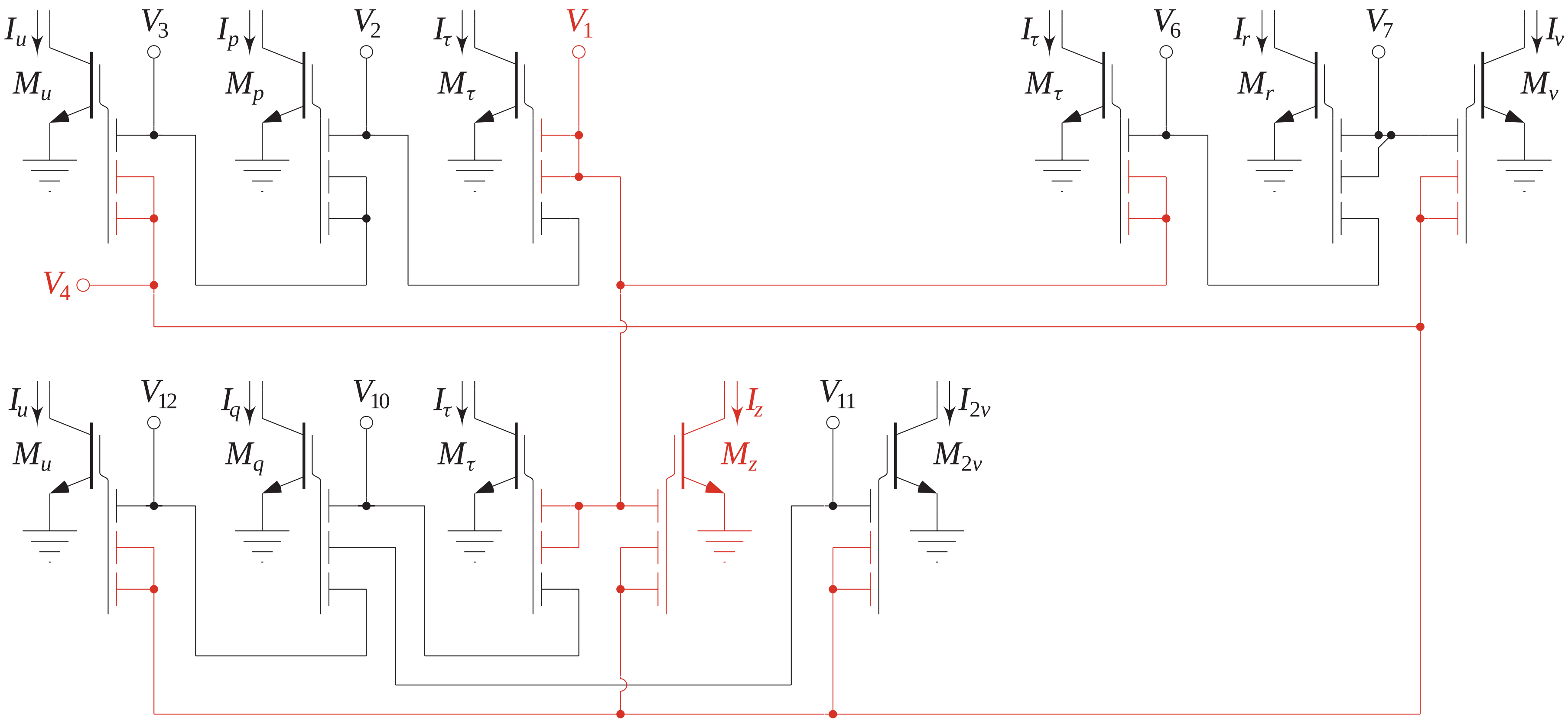

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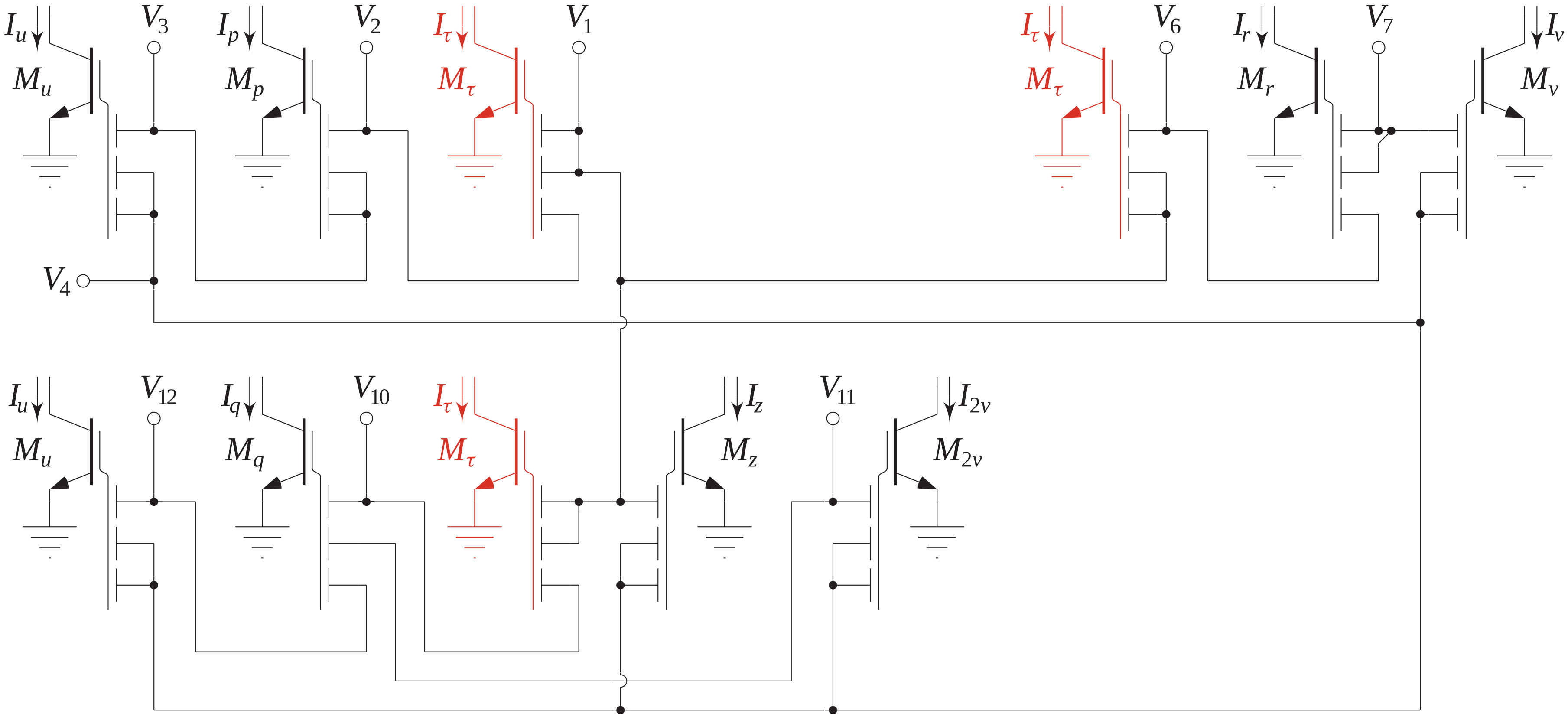

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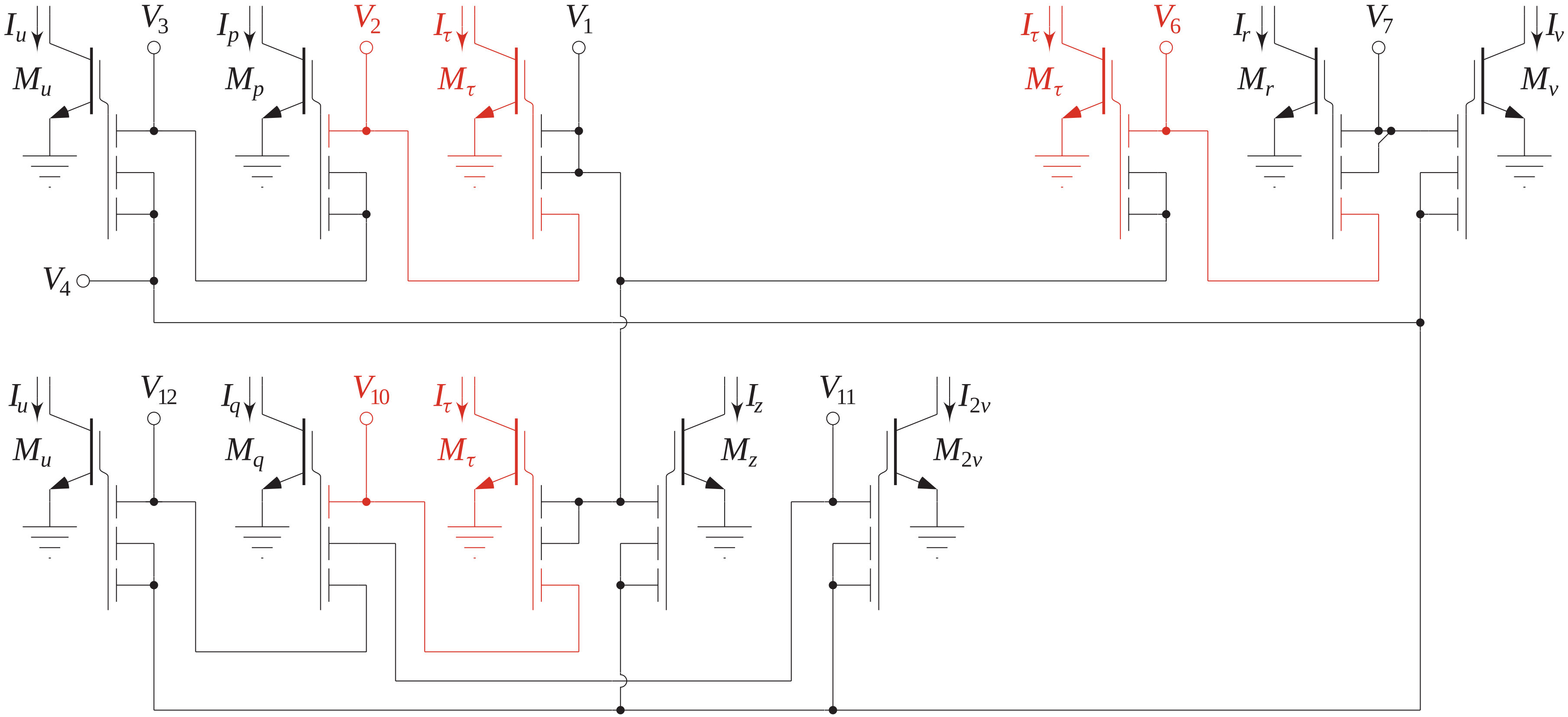

Dynamic MITE Network Synthesis: RMS-to-DC Converter

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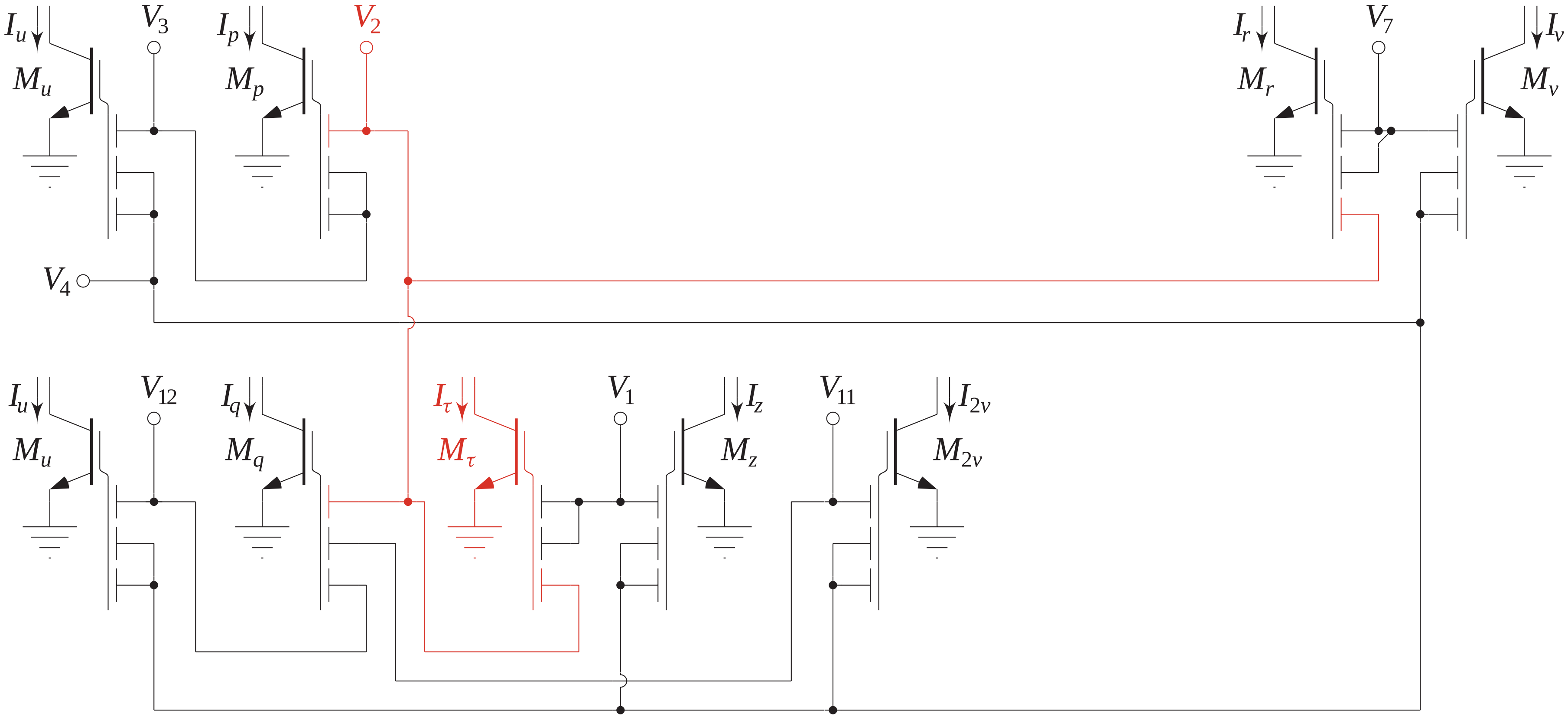

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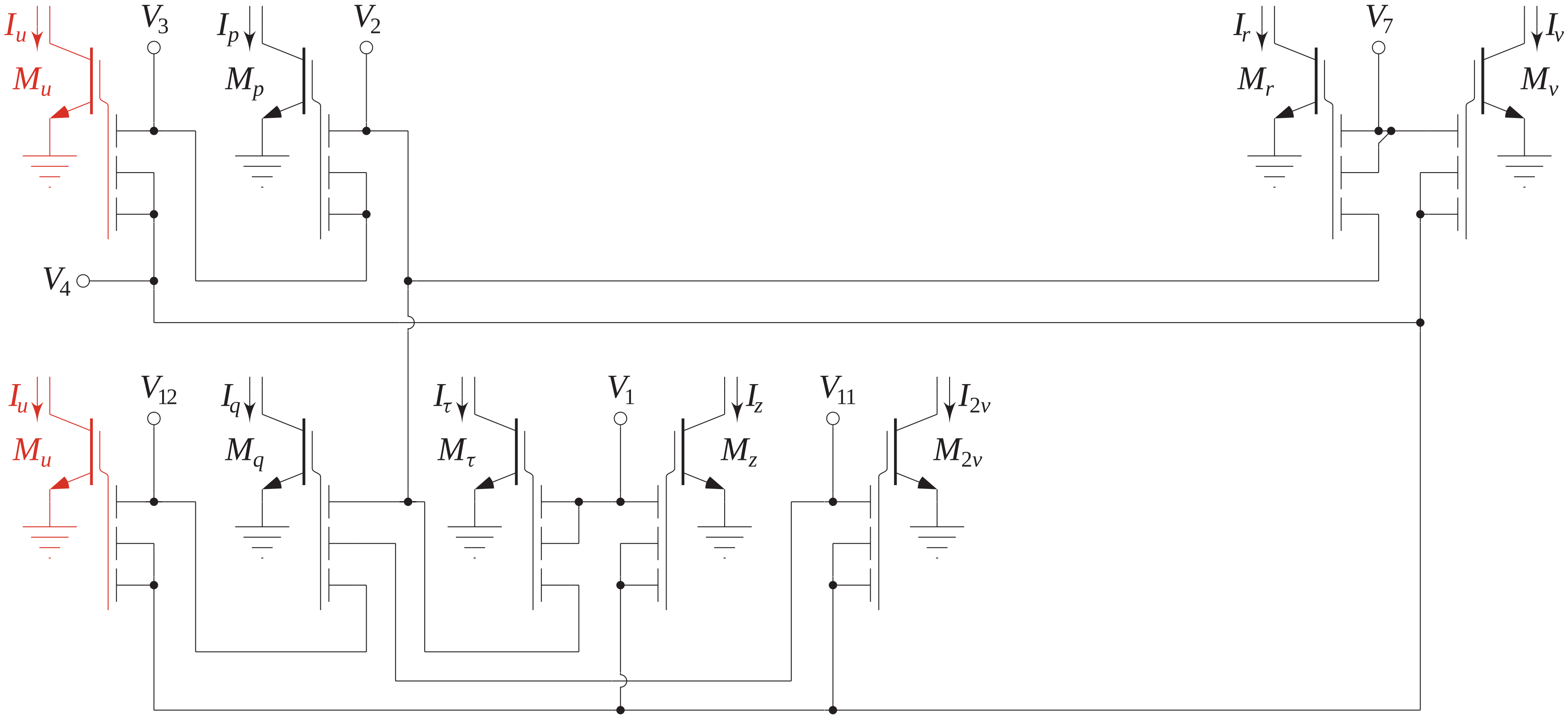

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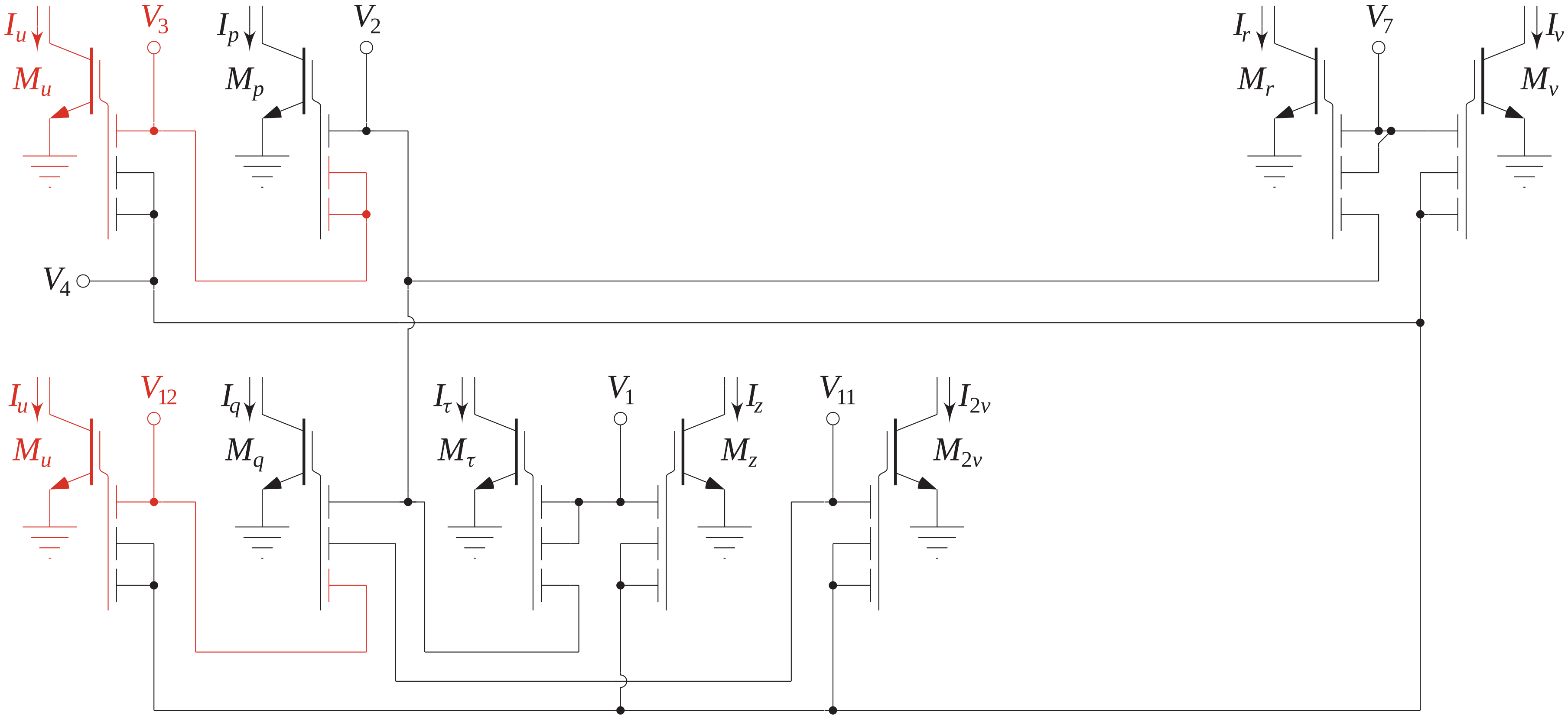

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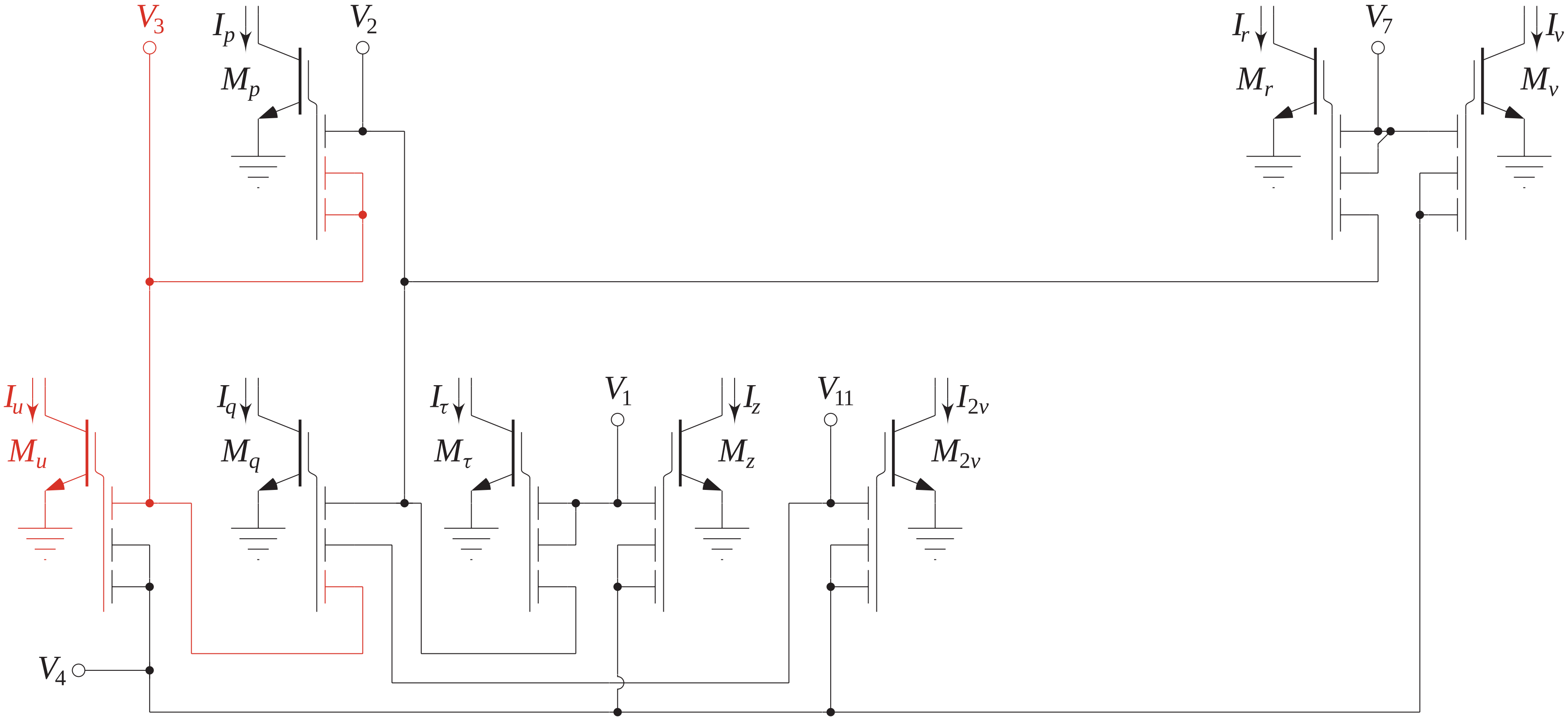

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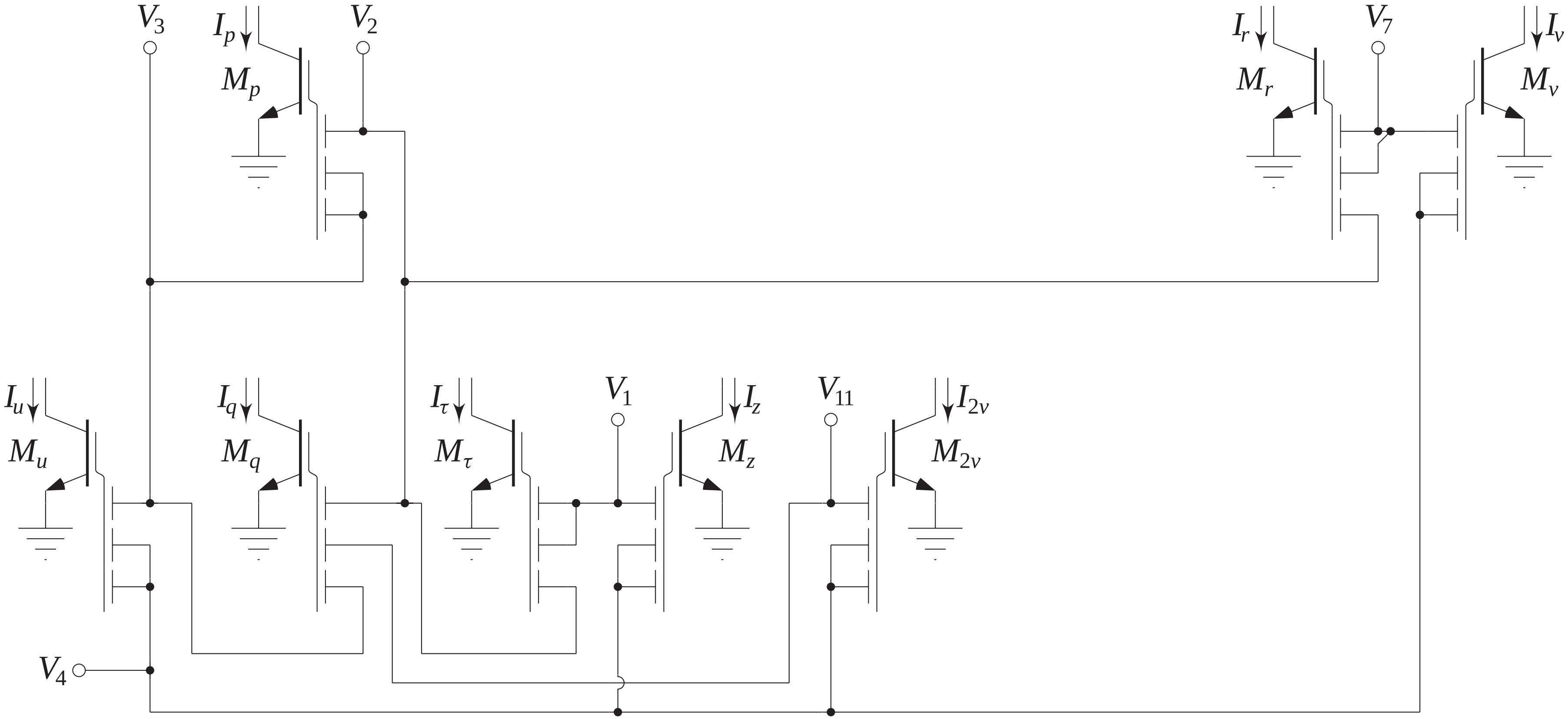

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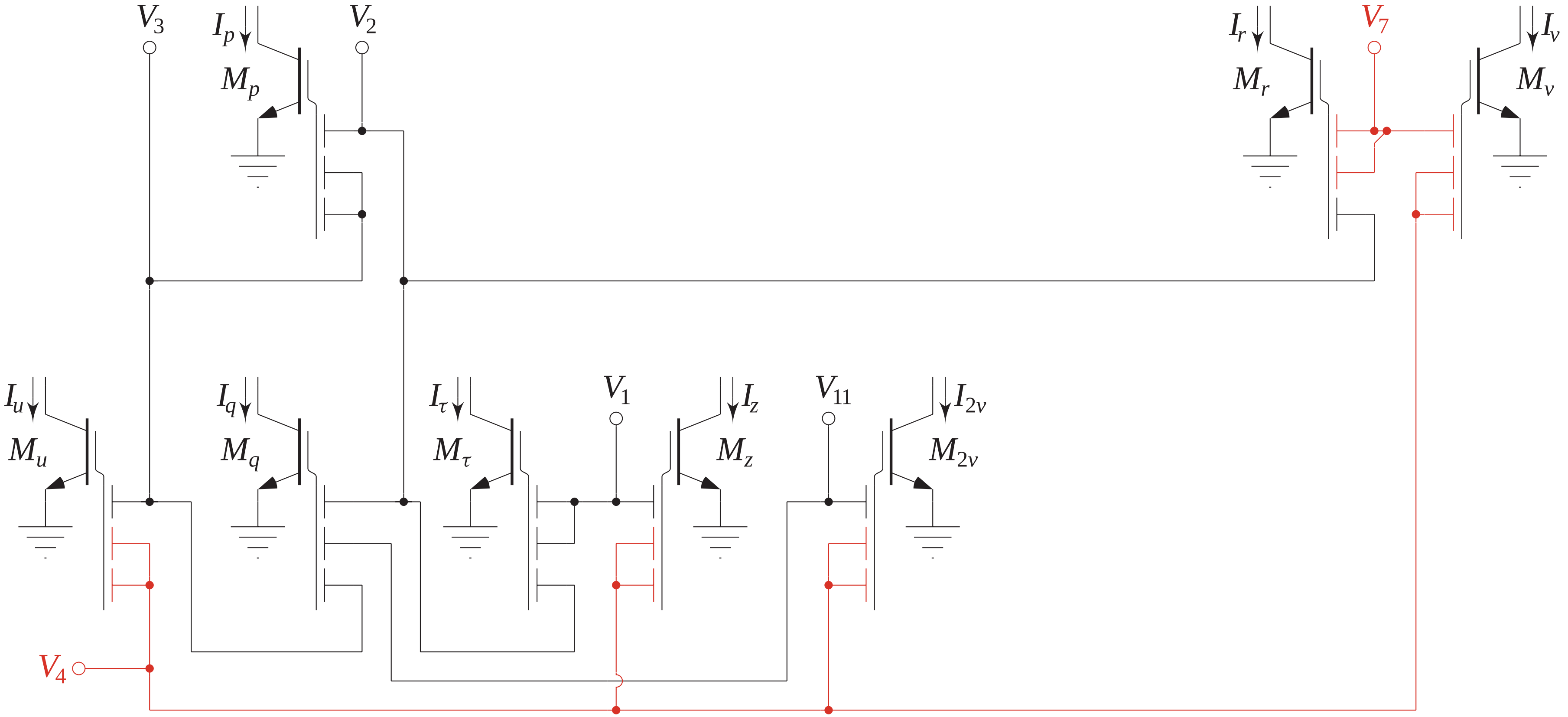

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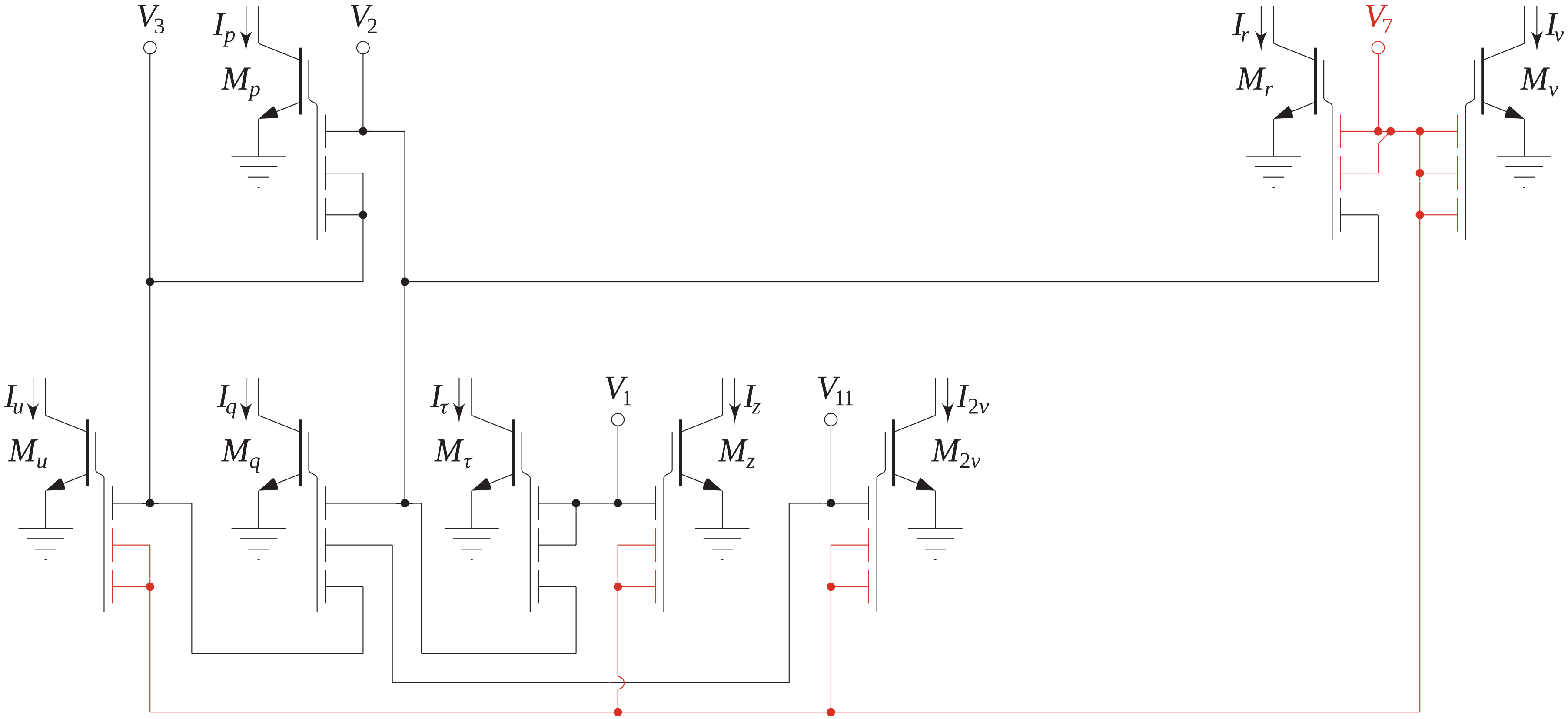

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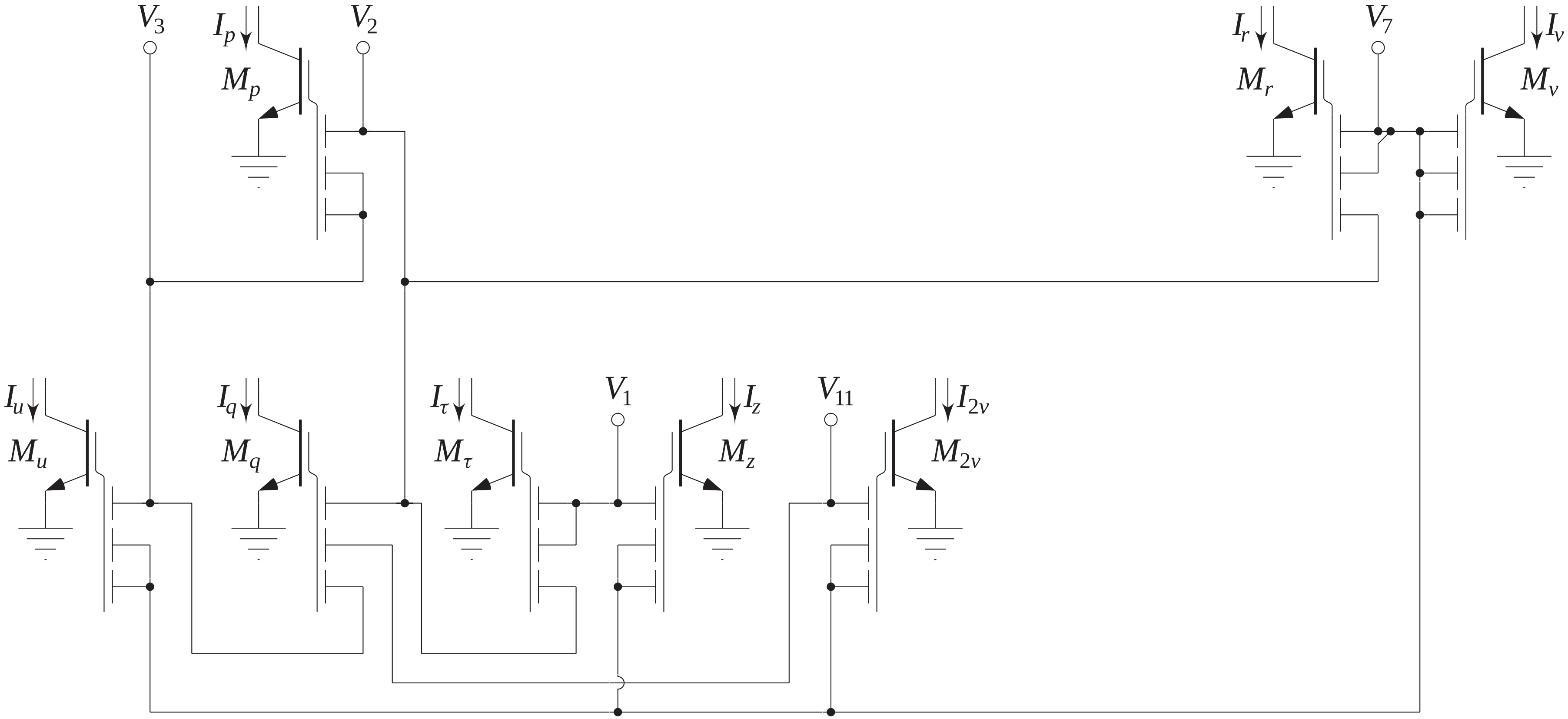

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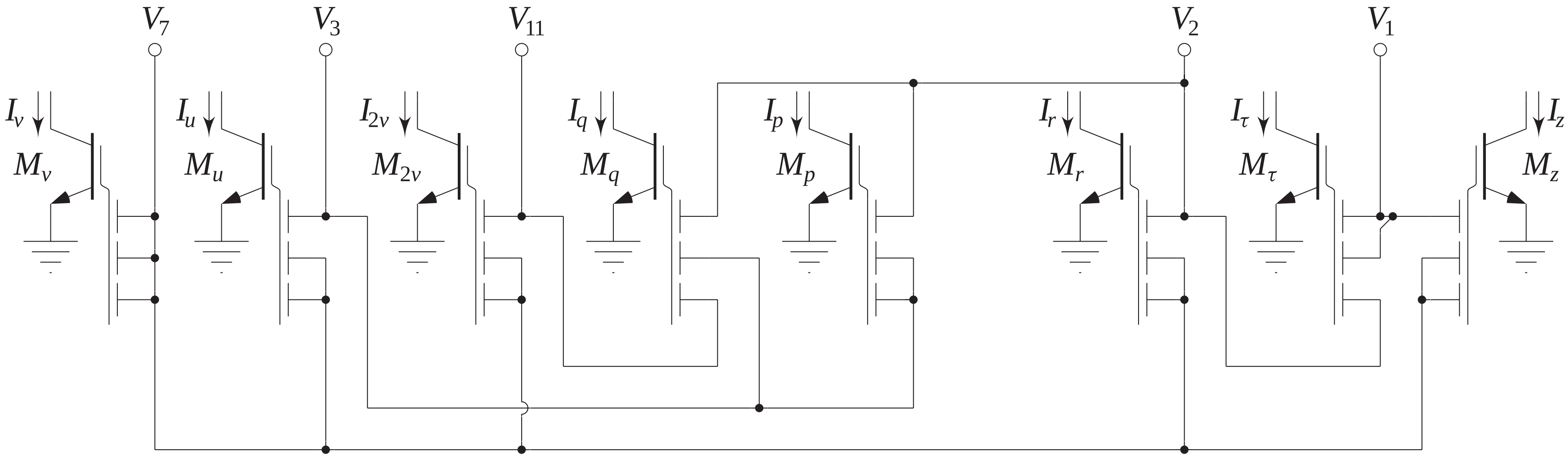

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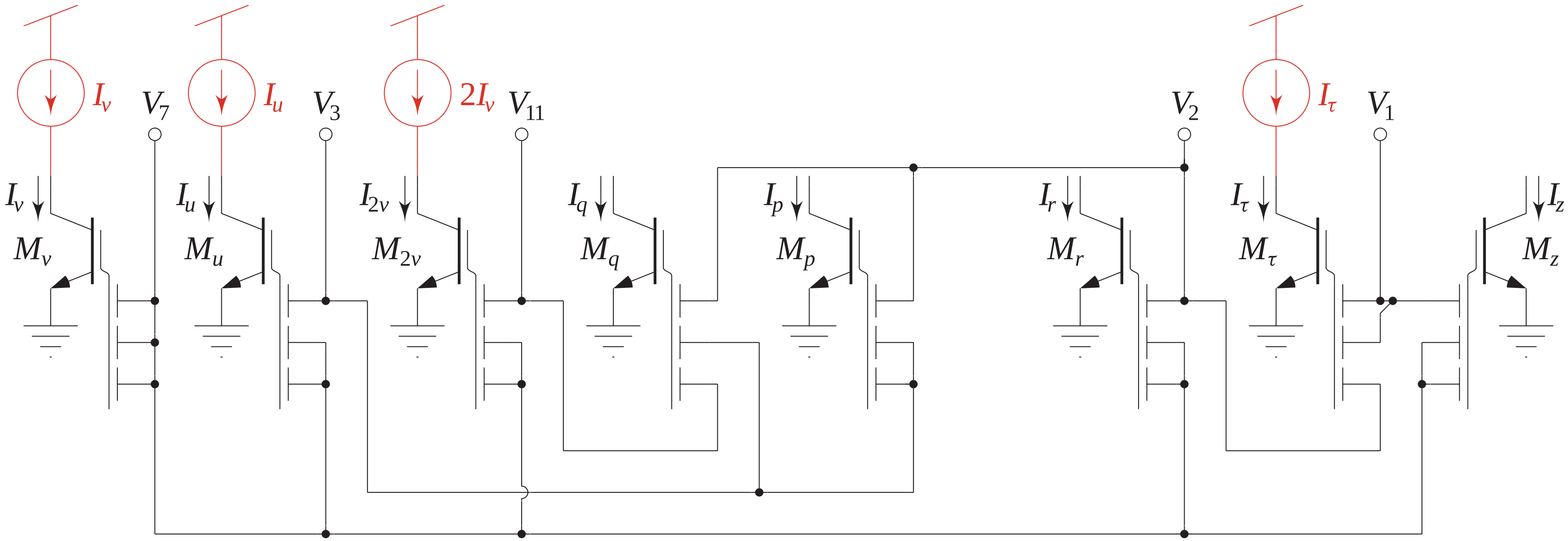

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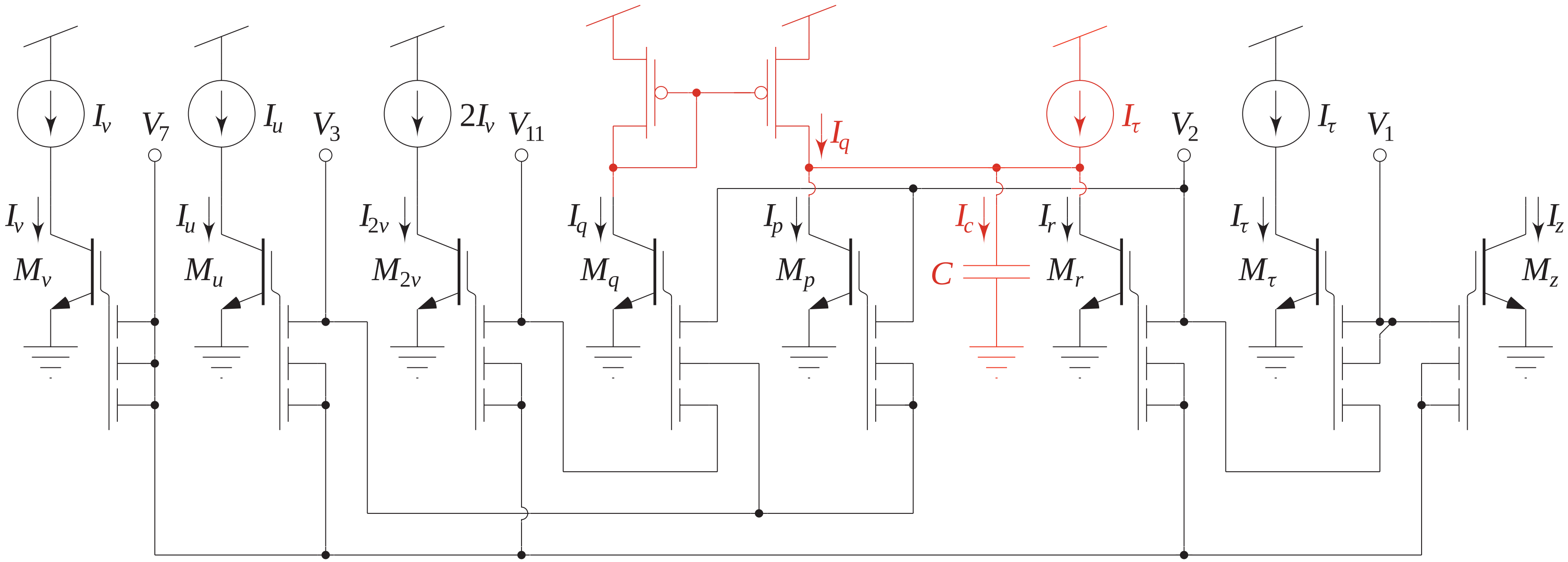

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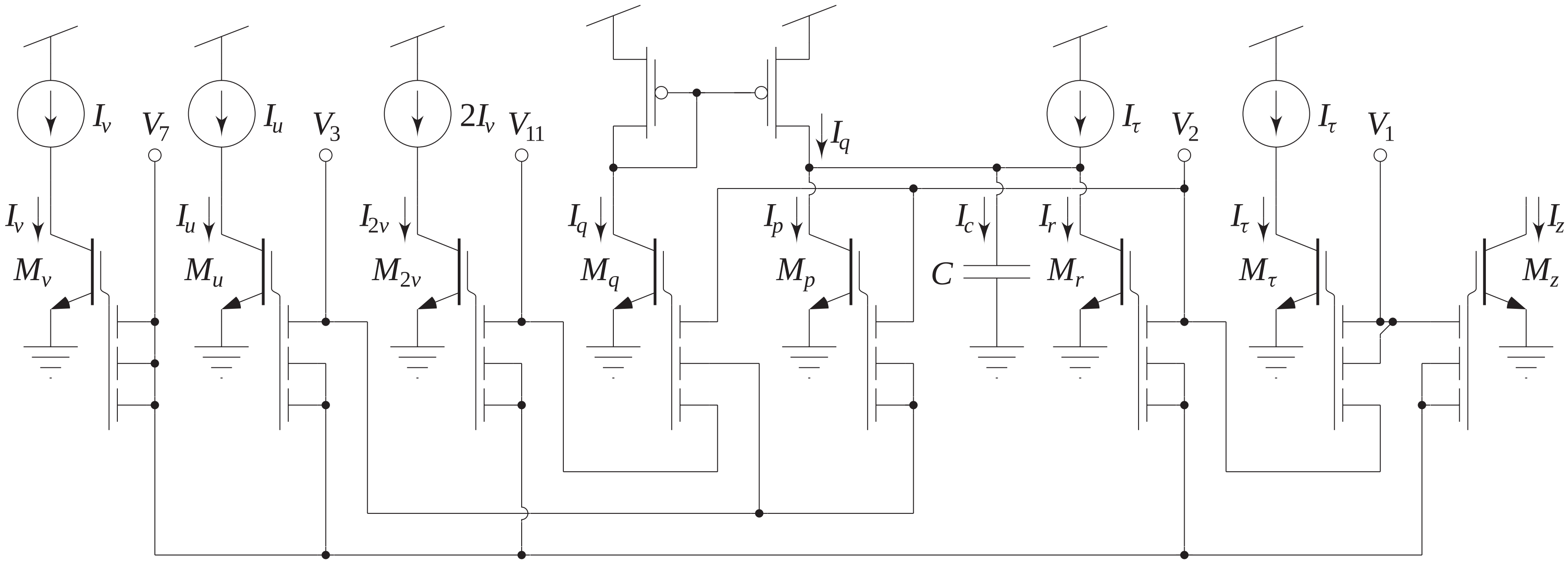

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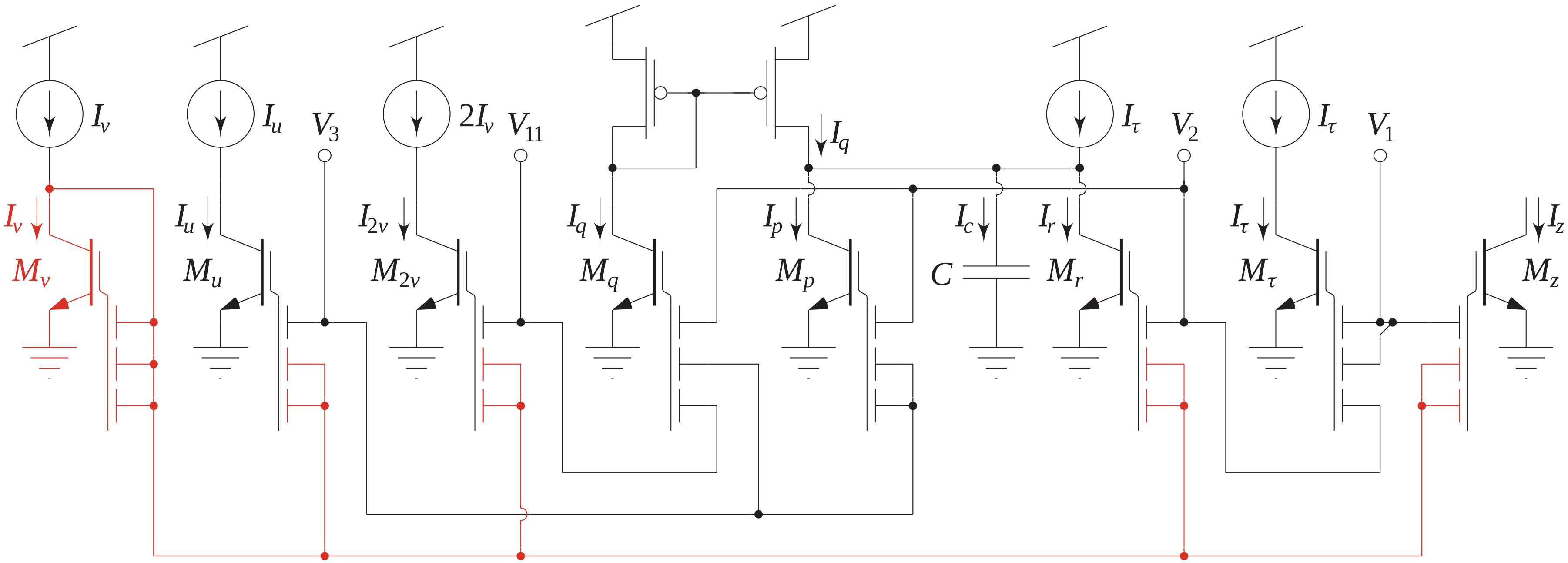

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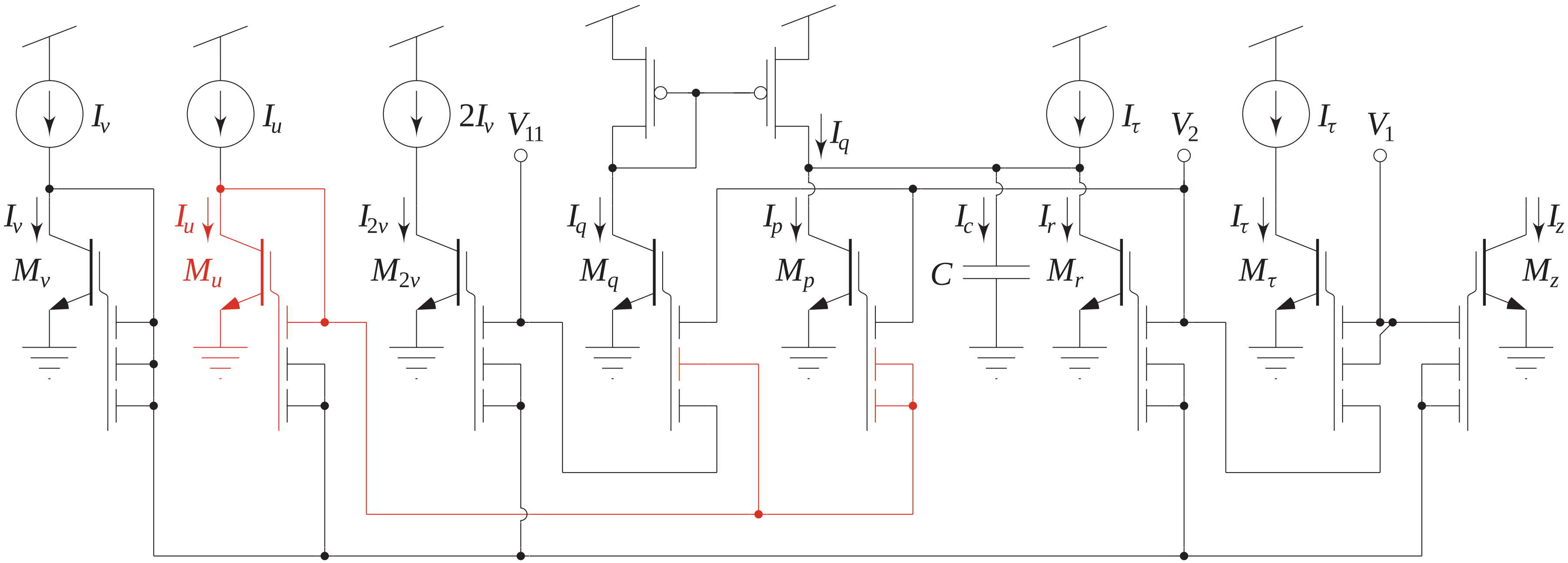

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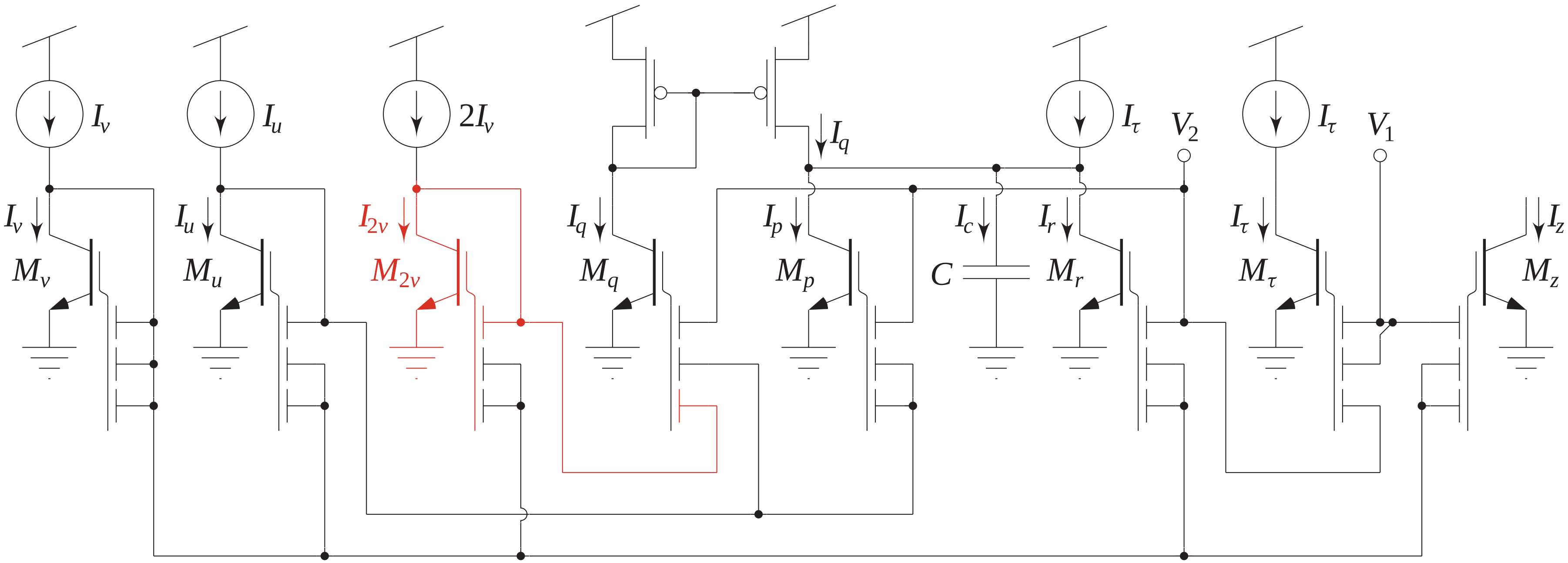

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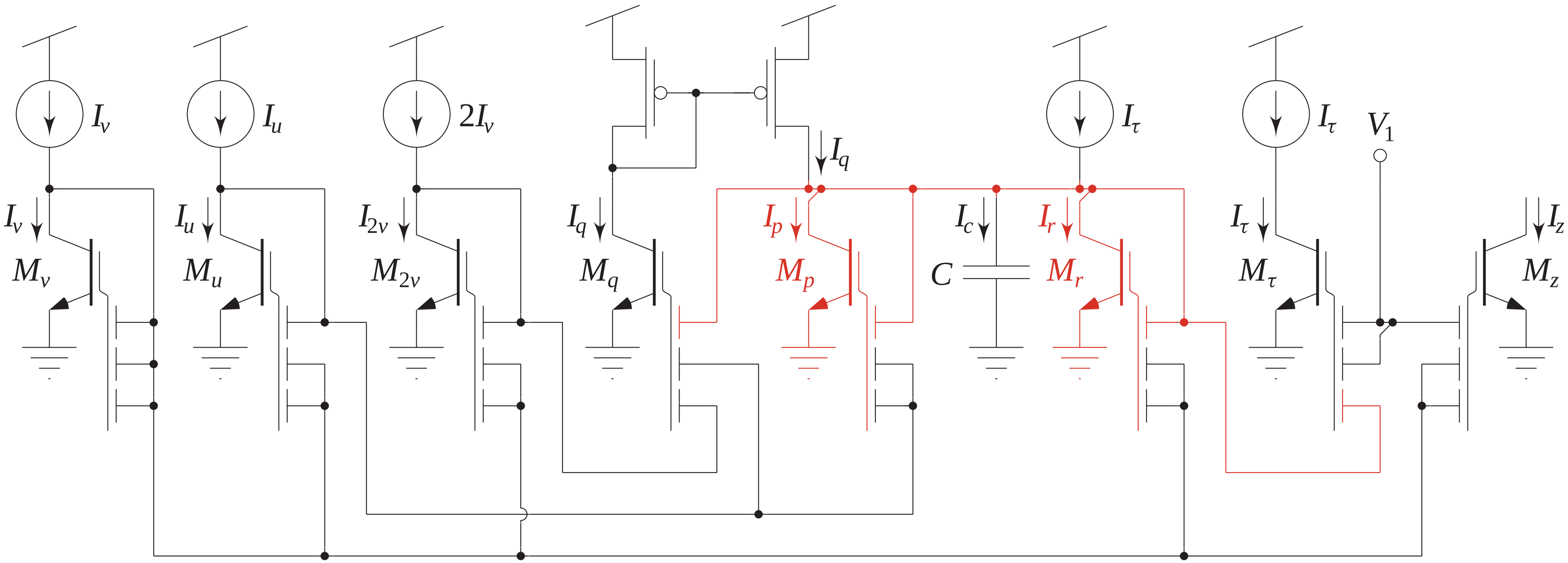

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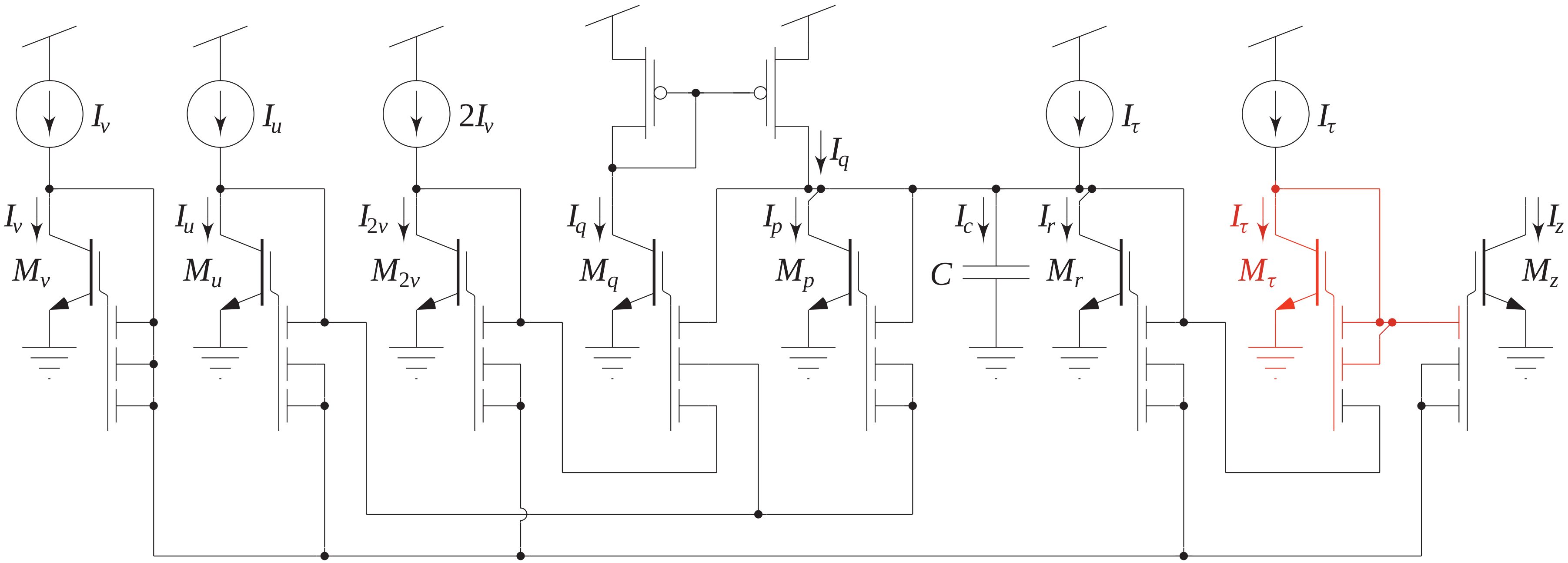

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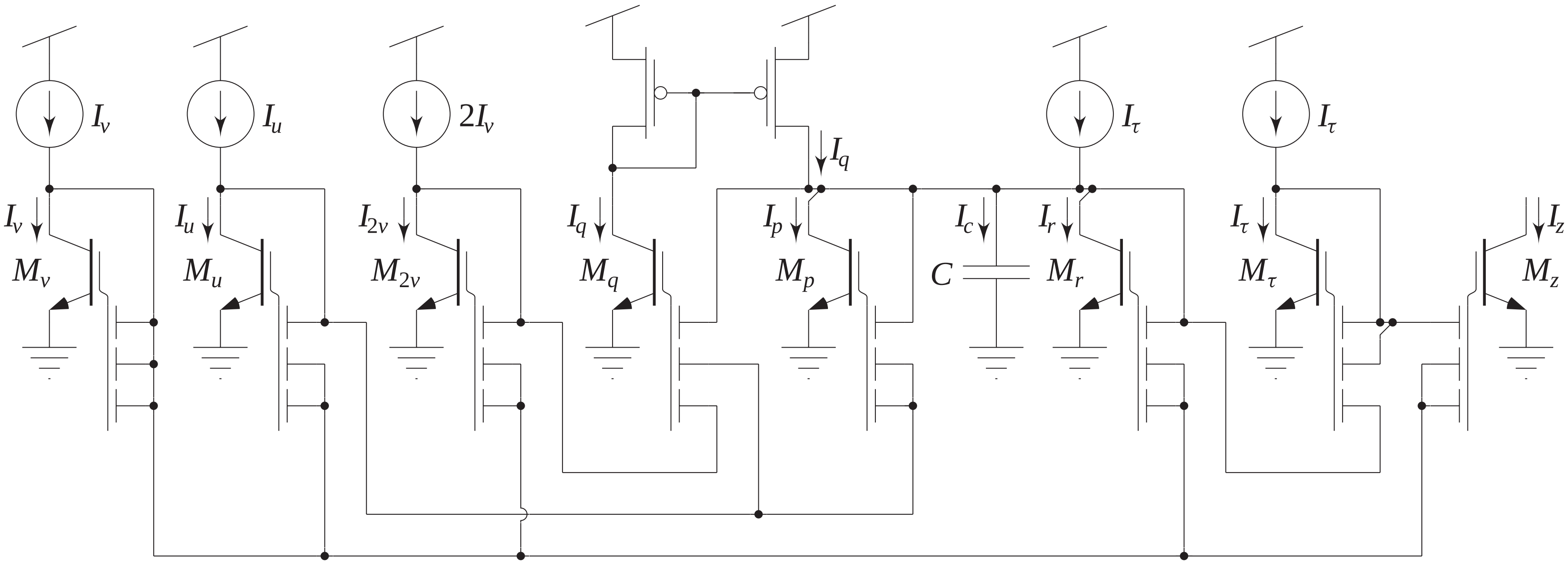

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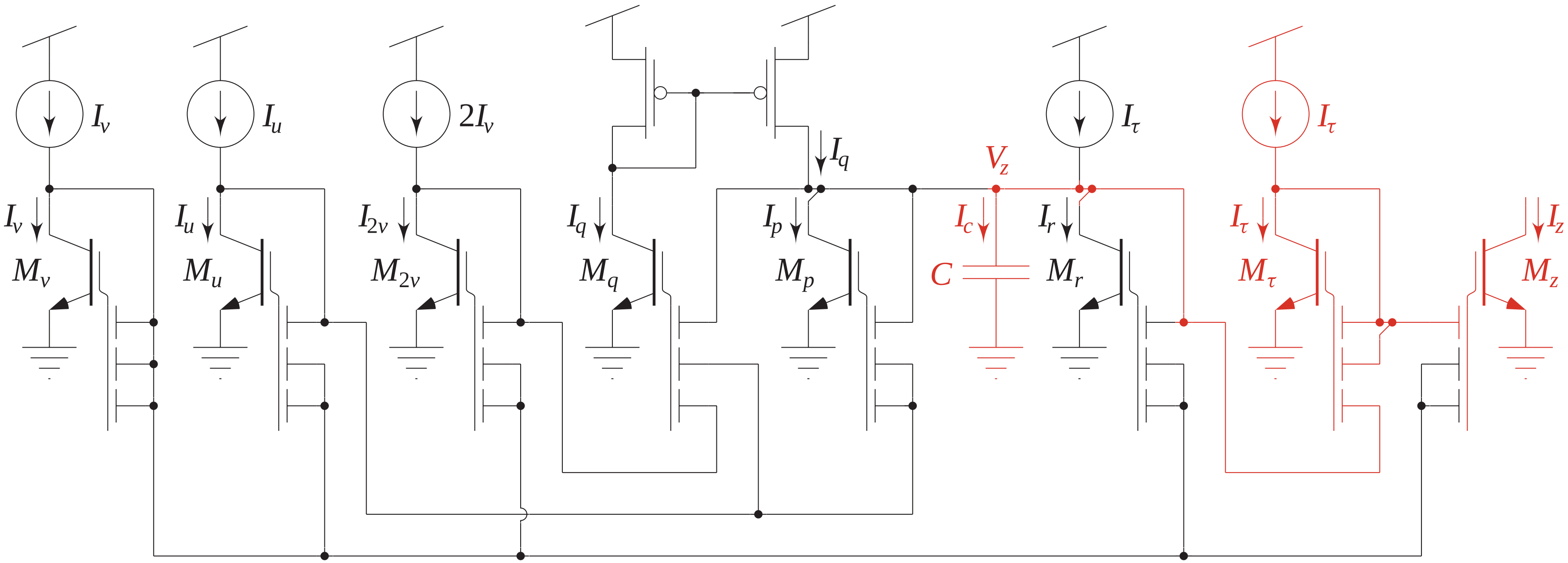

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