Análise de Sistemas de Potência

Aula 01: Introdução ao SEP

Prof. Lucas Melo

Universidade Federal do Ceará

28 de fevereiro de 2024

Sumário

Apresentação

Histórico do SEP

Constituição do SEP

Constituição do SEP no Brasil

Tendências do SEP

Lucas S. Melo, Dr.
Prof. Adjunto
Departamento de Engenharia Elétrica - UFC
Grupo de Redes Elétricas Inteligentes - GREI

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https://lucassm.pro

Áreas de Interesse na Pesquisa

- Recursos Energéticos Distribuídos - Modelagem, Simulação e Controle;
- Aplicação de Co-simulação em sistemas elétricos de potência;
- Aplicação de técnicas de otimização em sistemas elétricos de potência
- Automação/Proteção de Sistemas de Distribuição (IEC 61850);
- Sistemas de energia transativos.

Apresentação: GREI

GREI

Grupo de Redes Elétricas Inteligentes

Professores pesquisadores:

- Profa. Ruth Leão (UFC)
- Prof. Raimundo Furtado (UFC)
- Profa. Raquel Gregory (UFC)
- Prof. Lucas Melo (UFC)

Apresentação: GREI

Pesquisas desenvolvidas com projetos e artigos publicados nas áreas de:

- Automação da distribuição;
- Microrredes;
- Medição inteligente;
- Geração distribuída;
- Gestão de ativos;
- Armazenamento de energia; e
- Resposta à demanda;
- Entre outros.

Apresentação: GREI

Projetos atuais:

- CNPq: Co-simulação de Sistemas de Controle Transativos na Rede de Distribuição de Energia Elétrica;
- Funcap: Automação da Rede Elétrica;
- Funcap: Hidrogênio Verde.

Mais Informações

Página web com informações sobre as atividades do GREI

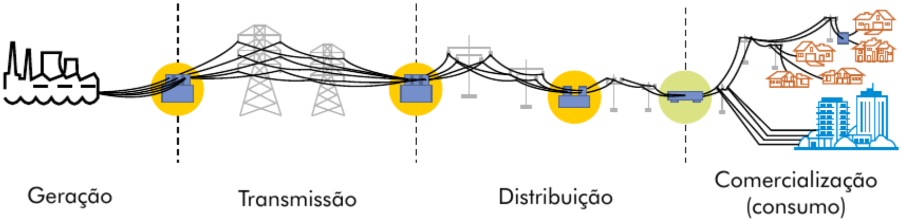
https://www.grei-ufc.github.io

Apresentação: ASP

Página web com todas as informações sobre a disciplina de ASP

https://www.lucassm.pro/teaching/ASP

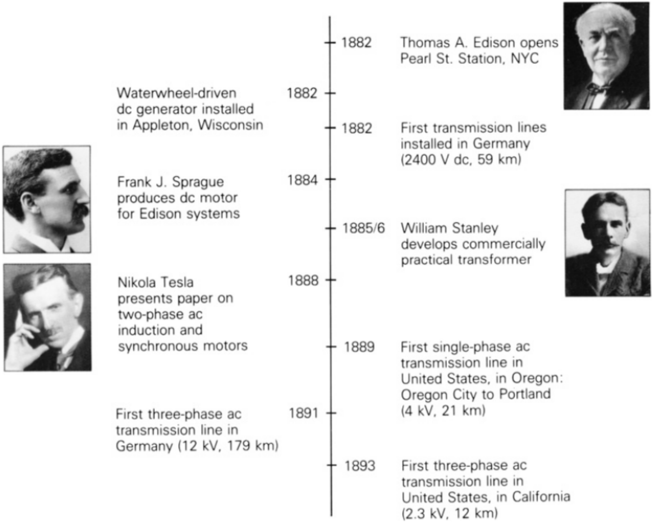
O Sistema Elétrico de Potência



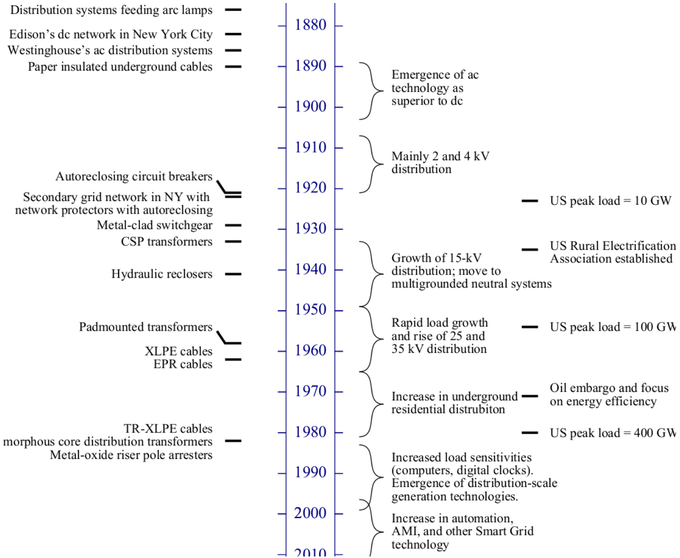
Histórico do SEP

- Telegraphic Lines (Fisrt Economic exploration of electricity): Fisrt trans-oceanic cable in (1858) 1866;
- DC systems;
- AC systems;
- Three-Phase Lines;
- Power Plants and Transmission Lines.

Histórico do SEP



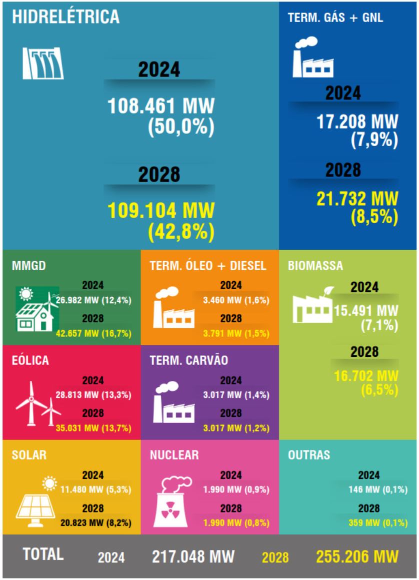
Histórico do SEP



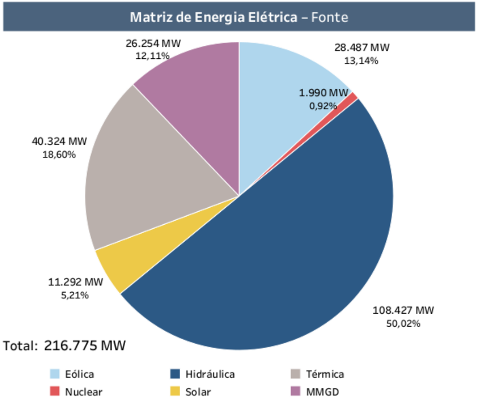
Generation

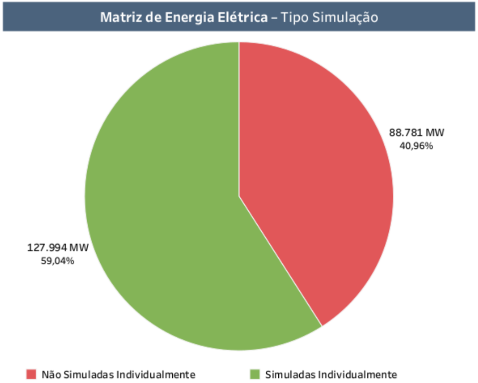
- Water Powered (Hydro) Turbine Plants;
- Steam Powered Turbine Plants: Coal, Nuclear, Gas;
- Renewable Energy: include conventional hydroelectric, geothermal, wood, wood waste, all municipal waste, landfill gas, other biomass, solar, and wind power.

EVOLUÇÃO DA CAPACIDADE INSTALADA NO SIN - FEVEREIRO 2024/ DEZEMBRO 2028

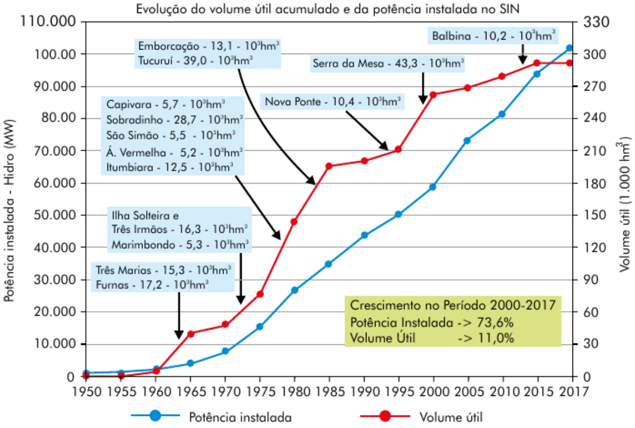


Generation

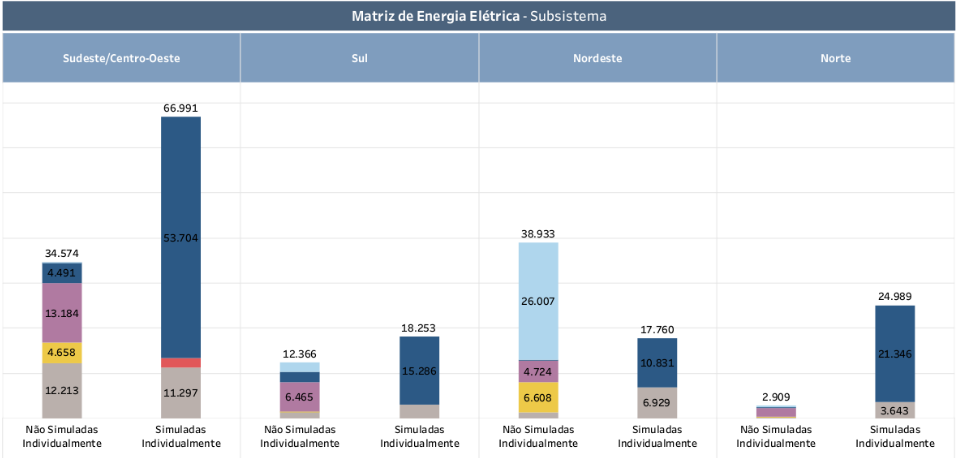

Matriz de Energia Elétrica – Fonte
26.254 MW
12,11%
28.487 MW
13,14%
1.990 MW
0,92%
40.324 MW
18,60%
11.292 MW
5,21%
108.427 MW
50,02%
Total: 216.775 MW
Eólica
Hidráulica
Térmica
Nuclear
Solar
MMGD


Matriz de Energia Elétrica – Tipo Simulação
88.781 MW
40,96%
127.994 MW
59,04%
Não Simuladas Individualmente
Simuladas Individualmente

Generation

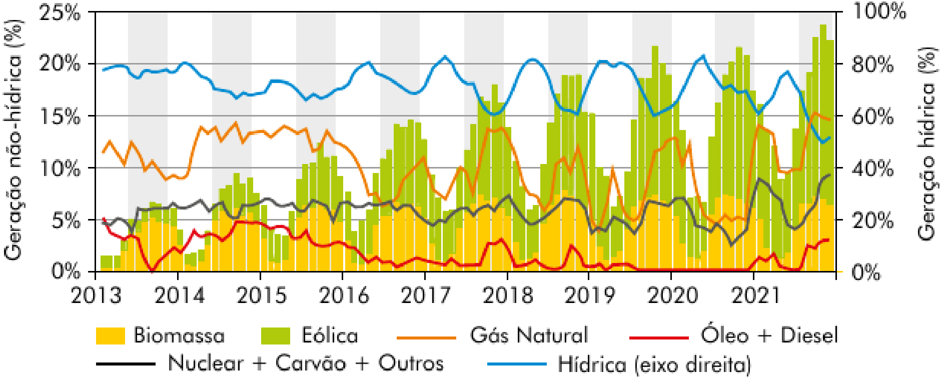

Evolução do volume útil acumulado e da potência instalada no SIN
Potência instalada - Hidro (MW)
Volume útil (1.000 hm³)
110.000
100.00
90.000
80.00
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0
330
300
270
240
210
180
150
120
90
60
30
0
1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2017
Emborcação - 13,1 - 10³hm³
Tucuruí - 39,0 - 10³hm³
Balbina - 10,2 - 10³hm³
Serra da Mesa - 43,3 - 10³hm³
Nova Ponte - 10,4 - 10³hm³
Capivara - 5,7 - 10³hm³
Sobradinho - 28,7 - 10³hm³
São Simão - 5,5 - 10³hm³
Á. Vermelha - 5,2 - 10³hm³
Itumbiara - 12,5 - 10³hm³
Ilha Solteira e
Três Irmãos - 16,3 - 10³hm³
Marimbondo - 5,3 - 10³hm³
Três Marias - 15,3 - 10³hm³
Furnas - 17,2 - 10³hm³
Crescimento no Período 2000-2017
Potência Instalada -> 73,6%
Volume Útil -> 11,0%
Potência instalada
Volume útil

Generation



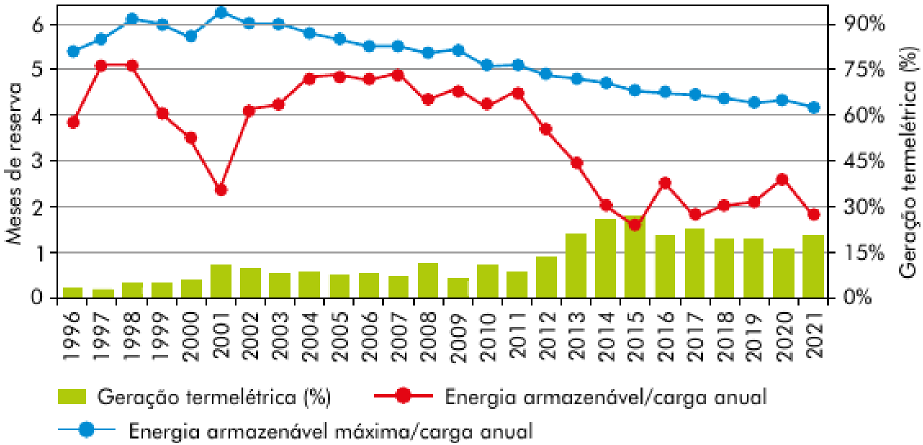
Matriz de Energia Elétrica - Subsistema
Sudeste/Centro-Oeste
Sul
Nordeste
Norte
34.574
4.491
13.184
4.658
12.213
66.991
53.704
11.297
12.366
6.465
18.253
15.286
38.933
26.007
4.724
6.608
17.760
10.831
6.929
2.909
24.989
21.346
3.643
Não Simuladas Individualmente
Simuladas Individualmente
Não Simuladas Individualmente
Simuladas Individualmente
Não Simuladas Individualmente
Simuladas Individualmente
Não Simuladas Individualmente
Simuladas Individualmente

Figura 3.4 Geração média mensal por fonte no SIN (%)



Fonte: FGV a partir de dados da CCEE

Figura 3.5 Perda da capacidade relativa de armazenamento dos reservatórios do SIN



Nota: A energia armazenada considera o nível dos reservatórios registrado no fim do período úmido (abril). A carga de 2021 considera a segunda revisão quadrimestral da carga (69.940 MWmed).

Generation

Sistema de Informações de Geração da ANEEL - SIGA

Standard Frequency

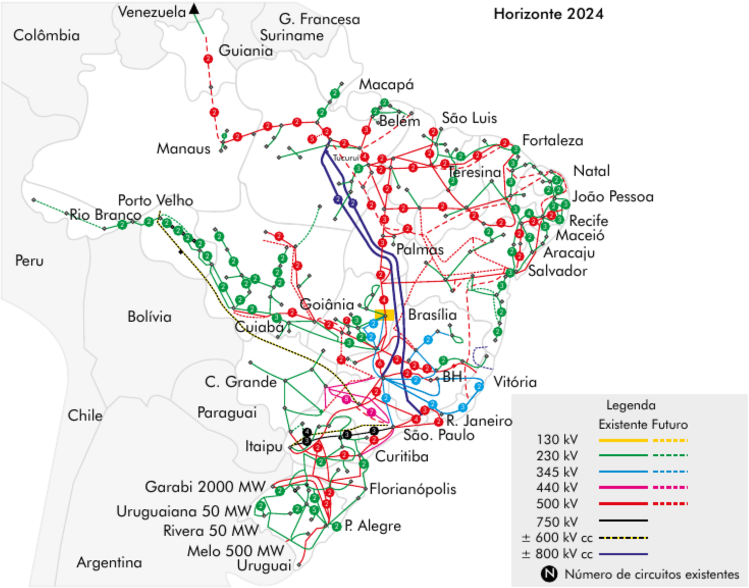
- The early ac systems operated at various frequencies including 25, 50, 60, and 133 Hz.
- In 1891, it was proposed that 60 Hz be the standard frequency in the United States.
- Today, the two standard frequencies for generation, transmission, and distribution of electric power in the world are:
- 60 Hz (in the United States, Canada, Mexico, and Brazil) and
- 50 Hz (in Europe, the former Soviet republics, China, South America, except Brazil, and India).
- In Japan, the western part of the country, including Kyoto, uses 60 Hz, while the eastern part, including Tokyo, uses 50 Hz.

Growth of the System: Generation, Transmision and Load

Análise de Alguns dados do SIN

Pico de carga do SIN: No dia 10 de março de 2022, foi registrado o recorde histórico de carga média diária do Sistema Interligado Nacional (SIN): 80.458 MW-méd.

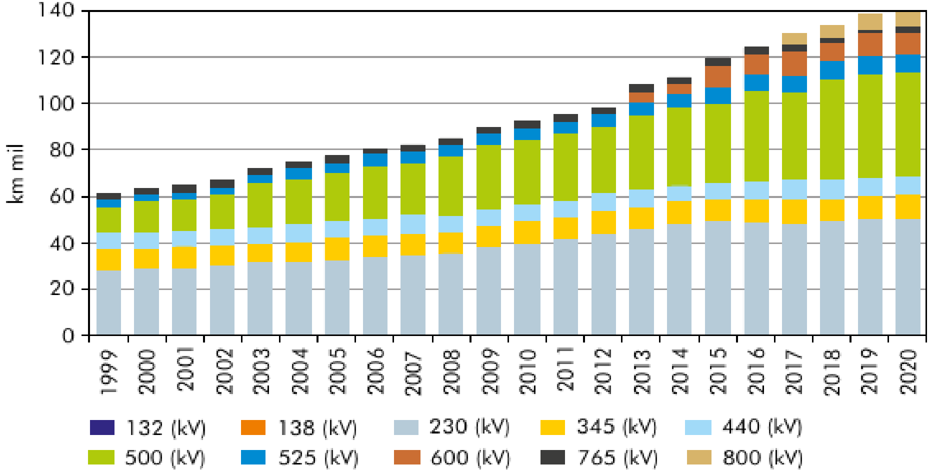
Nesse mesmo dia, a demanda máxima horária do SIN alcançou 88.617 MW, maior valor registrado desde o dia 1º de fevereiro de 2019.


Horizonte 2024
Venezuela
Colômbia
G. Francesa
Suriname
Guiania
Macapá
Belém
São Luis
Fortaleza
Manaus
Tucuruí
Teresina
Natal
João Pessoa
Recife
Maceió
Aracaju
Salvador
Porto Velho
Rio Branco
Peru
Palmas
Goiânia
Brasília
Bolívia
Cuiabá
BH
Vitória
C. Grande
Chile
Paraguai
R. Janeiro
São Paulo
Itaipu
Curitiba
Garabi 2000 MW
Florianópolis
Uruguaiana 50 MW
Rivera 50 MW
P. Alegre
Melo 500 MW
Uruguai
Argentina
Legenda
Existente Futuro
130 kV
230 kV
345 kV
440 kV
500 kV
750 kV
± 600 kV cc
± 800 kV cc
N Número de circuitos existentes

EXTENSÃO DA REDE BÁSICA DE TRANSMISSÃO

	2022	2027
230 kV	67.137 km	75.115 km
345 kV	10.491 km	11.406 km
440 kV	6.934 km	7.027 km
500/525 kV	70.044 km	97.039 km
600 kV	12.816 km	12.816 km
750 kV	2.683 km	2.683 km
800 kV	9.204 km	10.671 km
TOTAL	179.311 km	216.759 km

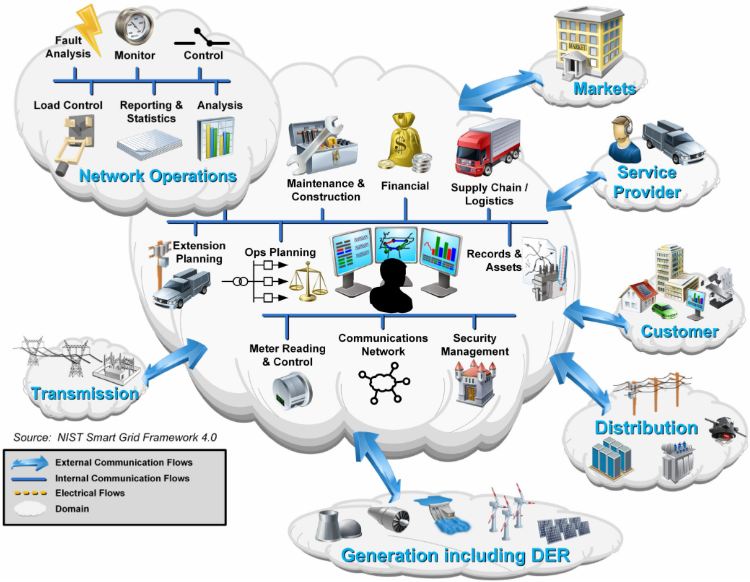
Figura 3.2 Evolução da extensão das linhas de transmissão do SIN, por nível de tensão



Present And Future Trends

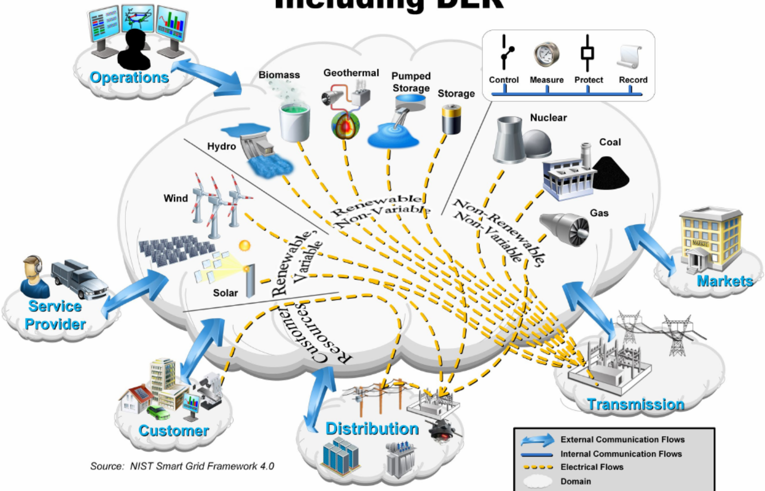
- **In Generation;**
- **In Transmission;**
- **In Distribution;**
- **The Smart Grids Concept;**
- **The Electricity Markets and the Energy Sector Liberalization.**

Operations



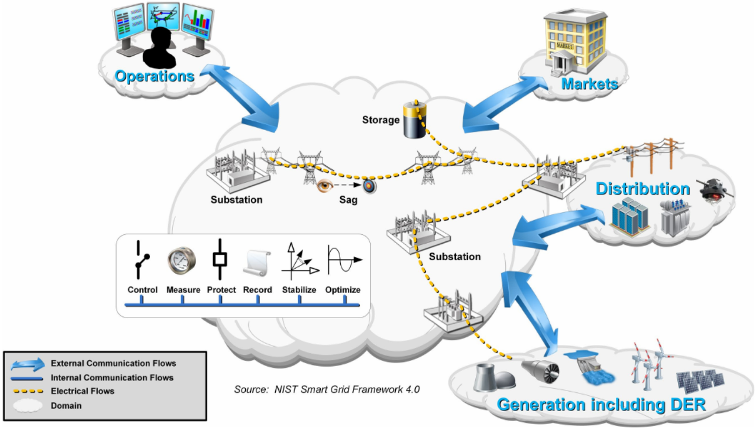
Source: NIST Smart Grid Framework 4.0

Generation Including DER



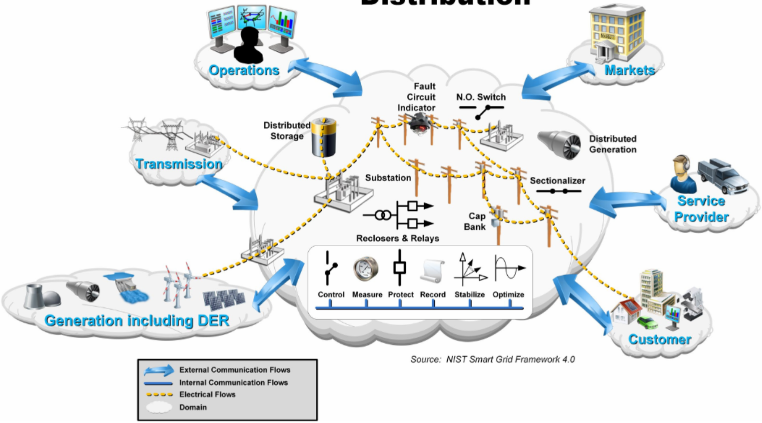
Source: NIST Smart Grid Framework 4.0

Transmission



Source: NIST Smart Grid Framework 4.0

Distribution



Source: NIST Smart Grid Framework 4.0

Computer in Power Systems

- Power Flow analisys;
- Short Circuit analisys;
- Stability analisys;
- Transient analisys.

Power Flow Analisys

Using Y_{bus} , the nodal equations for a power system network are written as:

$$\mathbf{I} = Y_{\text{bus}}\,\mathbf{V}$$

Where:

I is the N vector of source currents injected into each bus; and

V is the N vector of bus voltages.

Power Flow Analisys

In a more complete forme, the nodal equations for a power system network are written as:

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & \cdots & Y_{1N} \\ Y_{21} & Y_{22} & Y_{23} & \cdots & Y_{2N} \\ Y_{31} & Y_{32} & Y_{33} & \cdots & Y_{3N} \\ \vdots & \vdots & \vdots & & \vdots \\ Y_{N1} & Y_{N2} & Y_{N3} & \cdots & Y_{NN} \end{bmatrix} \begin{bmatrix} V_{10} \\ V_{20} \\ V_{30} \\ \vdots \\ V_{N0} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_N \end{bmatrix} \qquad (1)$$

Power Flow Analisys

For bus k, the k th equation in this matricial equation is given by:

$$I_k = \sum_{n=1}^{N} Y_{kn} V_n$$

The complex power delivered to bus k is

$$S_k = \mathrm{P}_k + j\mathrm{Q}_k = V_k I_k^*$$

Power Flow Analisys

Power flow solutions by Gauss-Seidel are based on nodal equations, with each current source I_k:

$$I_k = \sum_{n=1}^{N} Y_{kn} V_n$$

Inserted into power equations:

$$I_k = \sum_{n=1}^{N} Y_{kn} V_n = \frac{P_k - jQ_k}{V_k^*}$$

Power Flow Analisys

This give the closed form of Gauss-Seidel equations are:

$$V_k(i+1) = \frac{1}{Y_{kk}}\left[\frac{\mathrm{P}_k - j\mathrm{Q}_k}{V_k^*(i)} - \sum_{n=1}^{k-1} Y_{kn} V_n(i+1) - \sum_{n=k+1}^{N} Y_{kn} V_n(i)\right]$$

Power Flow Analisys

Now, using the current I_k definition and applying in complex power equation delivered to bus k:

$$I_k = \sum_{n=1}^{N} Y_{kn} V_n$$

$$S_k = \mathrm{P}_k + j\mathrm{Q}_k = V_k I_k^* = V_k \left[\sum_{n=1}^{N} Y_{kn} V_n \right]^* \qquad k = 1, 2, \ldots, N$$

Power Flow Analisys

With the following notation,

$$V_n = \mathrm{V}_n e^{j\delta_n}$$

$$Y_{kn} = \mathrm{Y}_{kn} e^{j\theta_{kn}} = G_{kn} + jB_{kn} \quad k, n = 1, 2, \ldots, N$$

This equation becomes:

$$\mathrm{P}_k + j\mathrm{Q}_k = \mathrm{V}_k \sum_{n=1}^{N} \mathrm{Y}_{kn} \, \mathrm{V}_n e^{j(\delta_k - \delta_n - \theta_{kn})}$$

Power Flow Analisys

Taking the real and imaginary parts of above equation, the *power balance equations* are written as either:

$$P_k = V_k \sum_{n=1}^{N} Y_{kn} V_n \cos(\delta_k - \delta_n - \theta_{kn})$$

$$Q_k = V_k \sum_{n=1}^{N} Y_{kn} V_n \sin(\delta_k - \delta_n - \theta_{kn}) \qquad k = 1, 2, \ldots, N$$

Power Flow Analisys

Or when the Y_{kn} is expressed in rectangular coordinates as:

$$\mathrm{P}_k = \mathrm{V}_k \sum_{n=1}^{N} V_n \left[G_{kn} \cos\left(\delta_k - \delta_n\right) + B_{kn} \sin\left(\delta_k - \delta_n\right) \right]$$

$$\mathrm{Q}_k = \mathrm{V}_k \sum_{n=1}^{N} V_n \left[G_{kn} \sin\left(\delta_k - \delta_n\right) - B_{kn} \cos\left(\delta_k - \delta_n\right) \right] \quad k = 1, 2, \ldots, N$$

Power flow solutions by *Newton-Raphson* are based on these nonlinear power flow equations, in polar or cartesian forms.

Power Flow Analisys

The Jacobian Equation:

$$
\mathbf{J} = \left[\begin{array}{ccc|ccc}
\frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_N} & \frac{\partial P_2}{\partial V_2} & \cdots & \frac{\partial P_2}{\partial V_N} \\
\vdots & & & \vdots & & \\
\frac{\partial P_N}{\partial \delta_2} & \cdots & \frac{\partial P_N}{\partial \delta_N} & \frac{\partial P_N}{\partial \mathbf{V}_2} & \cdots & \frac{\partial P_N}{\partial V_N} \\
\frac{\partial \mathbf{Q}_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_N} & \frac{\partial Q_2}{\partial \mathbf{V}_2} & \cdots & \frac{\partial Q_2}{\partial V_N} \\
\vdots & & & \vdots & & \\
\frac{\partial \mathbf{Q}_N}{\partial \delta_2} & \cdots & \frac{\partial \mathbf{Q}_N}{\partial \delta_N} & \frac{\partial \mathbf{Q}_N}{\partial \mathbf{V}_2} & \cdots & \frac{\partial Q_N}{\partial \mathbf{V}_N}
\end{array}\right]
$$

Power Flow Equations

Newton Raphson formulation:

$$\left[\begin{array}{c|c} \mathbf{J1}(i) & \mathbf{J2}(i) \\ \hline \mathbf{J3}(i) & \mathbf{J4}(i) \end{array}\right] \begin{bmatrix} \Delta\delta(i) \\ \Delta\mathbf{V}(i) \end{bmatrix} = \begin{bmatrix} \Delta\mathbf{P}(i) \\ \Delta\mathbf{Q}(i) \end{bmatrix}$$

Whith:

$$\mathbf{x}(i+1) = \begin{bmatrix} \delta(i+1) \\ \mathbf{V}(i+1) \end{bmatrix} = \begin{bmatrix} \delta(i) \\ \mathbf{V}(i) \end{bmatrix} + \begin{bmatrix} \Delta\delta(i) \\ \Delta\mathbf{V}(i) \end{bmatrix}$$

$$\Delta\mathbf{y}(i) = \begin{bmatrix} \Delta\mathbf{P}(i) \\ \Delta\mathbf{Q}(i) \end{bmatrix} = \begin{bmatrix} \mathbf{P} - \mathbf{P}[\mathbf{x}(i)] \\ \mathbf{Q} - \mathbf{Q}[\mathbf{x}(i)] \end{bmatrix}$$

Short Circuit Analisys

In short-circuit analisys, we have two distinct types of analisys:

- Symetrical Faults;
- Assymetrical Faults:

Symetrical faults type:

- Three Phase;
- Three Phase to Ground.

Assymetrical faults types:

- Phase to Ground;
- Phase to Phase;
- Phase to Phase to Ground.

Short Circuit Analisys

In short-circuit analisys, the system is modeled by its positive-sequence network, where:

- Lines and Transformers are represented by series reactances and
- synchronous machines are represented by constant-voltage sources behind subtransient reactances.

As before, all resistances, shunt admittances, and nonrotating impedance loads, and also for simplicity prefault load currents, are neglected.

Short Circuit Analisys

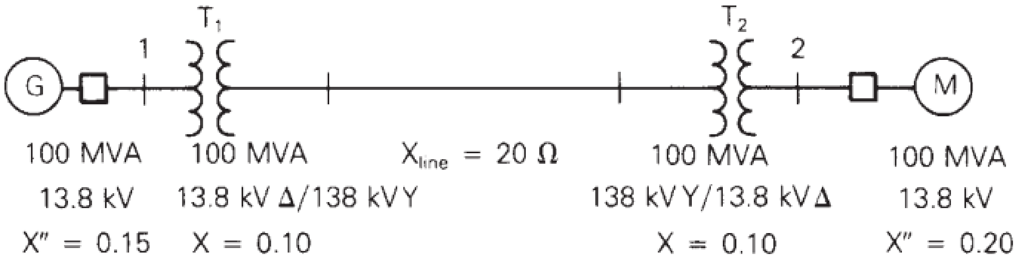
Consider a three-phase short circuit at any bus n. We use the superposition method to analysis this situation:

In the first circuit, all machine-voltage sources are short-circuited, and the only source is due to the prefault voltage at the fault. Writing nodal equations for the first circuit:

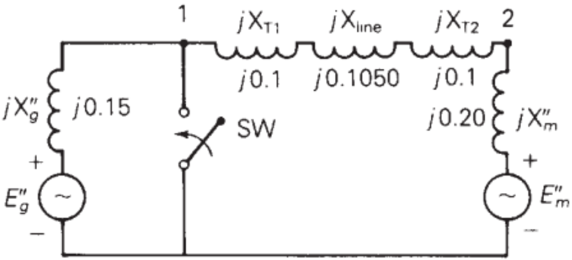
$$Y_{\text{bus}} E^{(1)} = I^{(1)}$$

Where Y_{bus} is the positive-sequence bus admittance matrix, $E^{(1)}$ is the vector of bus voltages, and $I^{(1)}$ is the vector of current sources. The superscript (1) denotes the first circuit.

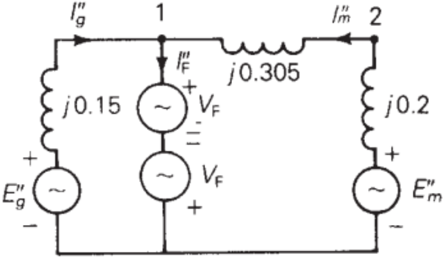
Short Circuit Analisys



Short Circuit Analisys

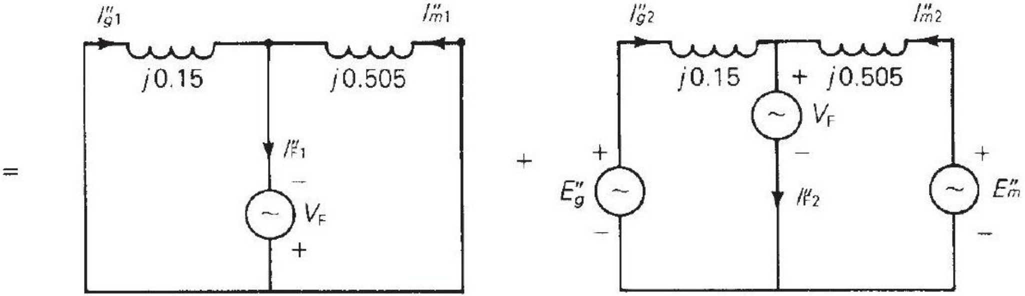


(a) Three-phase short circuit



(b) Short circuit represented by two opposing voltage sources

Short Circuit Analisys



Short Circuit Analisys

Solving:

$$Z_{\text{bus}} I^{(1)} = E^{(1)}$$

Where

$$Z_{\text{bus}} = Y_{\text{bus}}^{-1}$$

Z_{bus}, the inverse of Y_{bus}, is called the positive-sequence bus impedance matrix. Both Z_{bus} and Y_{bus} are symmetric matrices.

Short Circuit Analisys

Since the first circuit contains only one source, located at faulted bus n, the current source vector contains only one nonzero component, $I_n^{(1)} = -I''_{\mathrm{F}nn}$.

Also, the voltage at faulted bus n in the first circuit is $E_n^{(1)} = -V_{\mathrm{F}}$:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} & \cdots & Z_{2N} \\ \vdots & & & & & \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} & \cdots & Z_{nN} \\ \vdots & & & & & \\ Z_{N1} & Z_{N2} & \cdots & Z_{Nn} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I''_{\mathrm{F}n} \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} E_1^{(1)} \\ E_2^{(1)} \\ \vdots \\ -V_{\mathrm{F}} \\ \vdots \\ E_N^{(1)} \end{bmatrix}$$

Short Circuit Analisys

The minus sign associated with the current source in (7.4.4) indicates that the current injected into bus n is the negative of I''_{Fn}, since I''_{Fn} flows away from bus n to the neutral.

In this way, the subtransient fault current is given by:

$$I''_{\mathrm{F}n} = \frac{V_{\mathrm{F}}}{Z_{nn}}$$

Also, the voltage at any bus k in the first circuit is:

$$E_k^{(1)} = Z_{kn}\left(-I''_{\mathrm{F}n}\right) = \frac{-Z_{kn}}{Z_{nn}} V_{\mathrm{F}}$$

Short Circuit Analisys

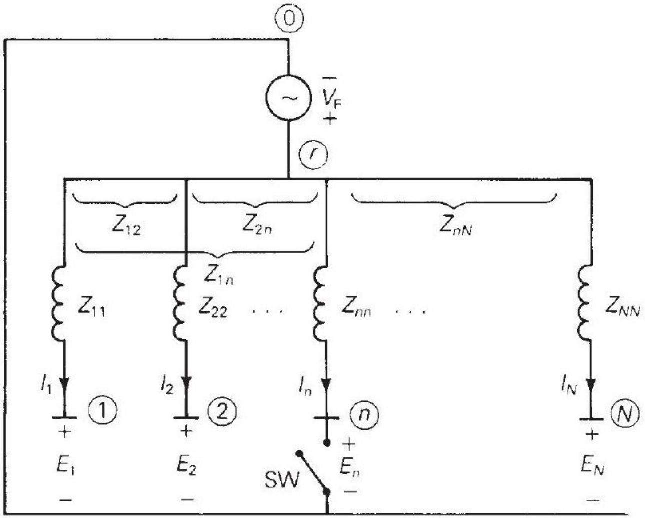
The second circuit represents the prefault conditions.

Neglecting prefault load current, all voltages throughout the second circuit are equal to the prefault voltage; that is, $E^{(2)} = V_F$ for each bus k.

Applying superposition, we have:

$$\begin{aligned} E_k = E_k^{(1)} + E_k^{(2)} &= \frac{-Z_{kn}}{Z_{nn}} V_F + V_F \\ &= \left(1 - \frac{Z_{kn}}{Z_{nn}}\right) V_F \quad k = 1, 2, \ldots, N \end{aligned}$$

Short Circuit Analisys



Short Circuit Analisys

The Figure above shows a bus impedance equivalent circuit that illustrates the short-circuit currents in an N-bus system.

This circuit is given the name rake equivalent in Neuenswander [5] due to its shape, which is similar to a garden rake.

The diagonal elements $Z_{11}, Z_{22}, \ldots, Z_{NN}$ of the bus impedance matrix, which are the self-impedances, are shown in Figure too.

The off-diagonal elements, or the mutual impedances, are indicated by the brackets in the figure.

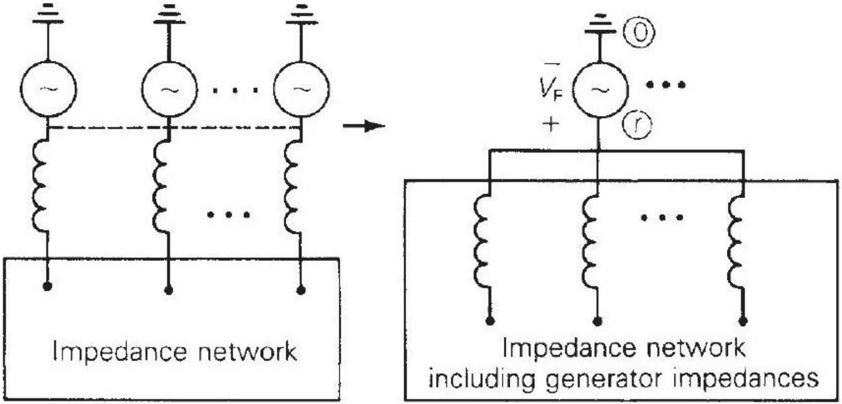
Short Circuit Analisys

Neglecting prefault load currents, the internal voltage sources of all synchronous machines are equal both in magnitude and phase.

As such, they can be connected, as shown in the same Figure, and replaced by one equivalent source V_{F} from neutral bus 0 to a references bus, denoted r.

This equivalent source is also shown in the rake equivalent of Figure.

Short Circuit Analisys



Short Circuit Analisys

Using Z_{bus} , the fault currents in Figure are given by:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} & \cdots & Z_{2N} \\ \vdots & & & & & \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} & \cdots & Z_{nN} \\ \vdots & & & & & \\ Z_{N1} & Z_{N2} & \cdots & Z_{Nn} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} V_{\text{F}} - E_1 \\ V_{\text{F}} - E_2 \\ \vdots \\ V_{\text{F}} - E_n \\ \vdots \\ V_{\text{F}} - E_N \end{bmatrix}$$

Where $I_1, I_2, \ldots$ are the branch currents and $(V_{\text{F}} - E_1), (V_{\text{F}} - E_2), \ldots$ are the voltages across the branches.

Short Circuit Analisys

If switch SW in Figure is open, all currents are zero and the voltage at each bus with respect to the neutral equals V_F. This corresponds to prefault conditions, neglecting prefault load currents.

If switch SW *is closed*, corresponding to a short circuit at bus n, $E_n = 0$ and all currents except I_n remain zero. The fault current is:

$$I''_{\mathrm{F}n} = I_n = V_\mathrm{F}/Z_{nn}$$

Short Circuit Analisys

This fault current also induces a voltage drop $Z_{kn}I_n = (Z_{kn}/Z_{nn})\, V_F$ across each branch k.

The voltage at bus k with respect to the neutral then equals V_F minus this voltage drop.

As shown by Figure, subtransient fault currents throughout an N-bus system can be determined from the bus impedance matrix and the prefault voltage.

Short Circuit Analisys

Concluding:

Z_{bus} can be computed by first constructing Y_{bus}, via nodal equations, and then inverting Y_{bus}.

Once Z_{bus} has been obtained, these fault currents are easily computed.