Power Flow Algorithm for Multi-Terminal Unbalanced Hybrid AC/DC Distribution Network

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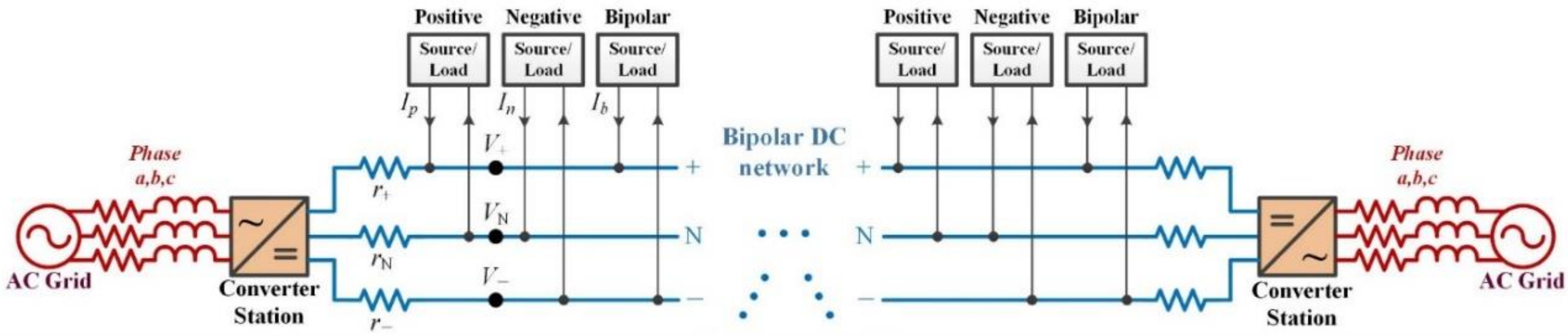
Introduction

✔ South Korean government has decided to invest $222 million to develop hybrid AC/DC components, operation methods, and pilot plant construction. Among power system studies, a power flow algorithm is essential for steady-state analysis.



Mathematical Model

AC grid

- Unbalanced three-phase AC network

$$\begin{pmatrix} P_i^a + jQ_i^a \\ P_i^b + jQ_i^b \\ P_i^c + jQ_i^c \end{pmatrix} = \begin{pmatrix} V_i^a \measuredangle \theta_i^a \\ V_i^b \measuredangle \theta_i^b \\ V_i^c \measuredangle \theta_i^c \end{pmatrix} \odot \sum_j \begin{pmatrix} Y_{ij}^{aa} & Y_{ij}^{ab} & Y_{ij}^{ac} \\ Y_{ij}^{ba} & Y_{ij}^{bb} & Y_{ij}^{bc} \\ Y_{ij}^{ca} & Y_{ij}^{cb} & Y_{ij}^{cc} \end{pmatrix} \begin{pmatrix} V_j^a \measuredangle \theta_j^a \\ V_j^b \measuredangle \theta_j^b \\ V_j^c \measuredangle \theta_j^c \end{pmatrix}$$

$$\text{where, } P_i^\phi + jQ_i^\phi = \left(P_{G,i}^\phi - P_{L,i}^\phi\right) + j\left(Q_{G,i}^\phi - Q_{L,i}^\phi\right)$$

DC grid

- Unbalanced bipolar DC network

$$\begin{pmatrix} I_{inj,+} \\ I_{inj,\mathrm{N}} \\ I_{inj,-} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & -1 \\ 0 & -1 & -1 \end{pmatrix} \begin{pmatrix} I_{G,p} - I_{L,p} \\ I_{G,b} - I_{L,b} \\ I_{G,n} - I_{L,n} \end{pmatrix} \qquad \text{where, } I_{inj,\varphi} = G_\varphi V_\varphi$$

Converter Station

- Active power [Bipolar DC Voltage Balancer]

① $V_{p,i} = V_{n,i} = V^n$

② $\begin{cases} V_{p,i} = V_{n,i} \\ P_{CS,dc} = P_{CS,dc}^0 + k_{CS,p}\left(V_{dc}^n - \dfrac{(V_{+,i} - V_{-,i})}{2}\right) \end{cases}$

③ $P_{CS,dc} = P_{CS,p}^0 + P_{CS,n}^0$

- Reactive power

① $V_{a/b/c} = V^n$ ② $Q_{CS,ac} = Q_{CS,ac}^0 + k_{CS,q}\left(V_{ac}^0 - V_i^1\right)$

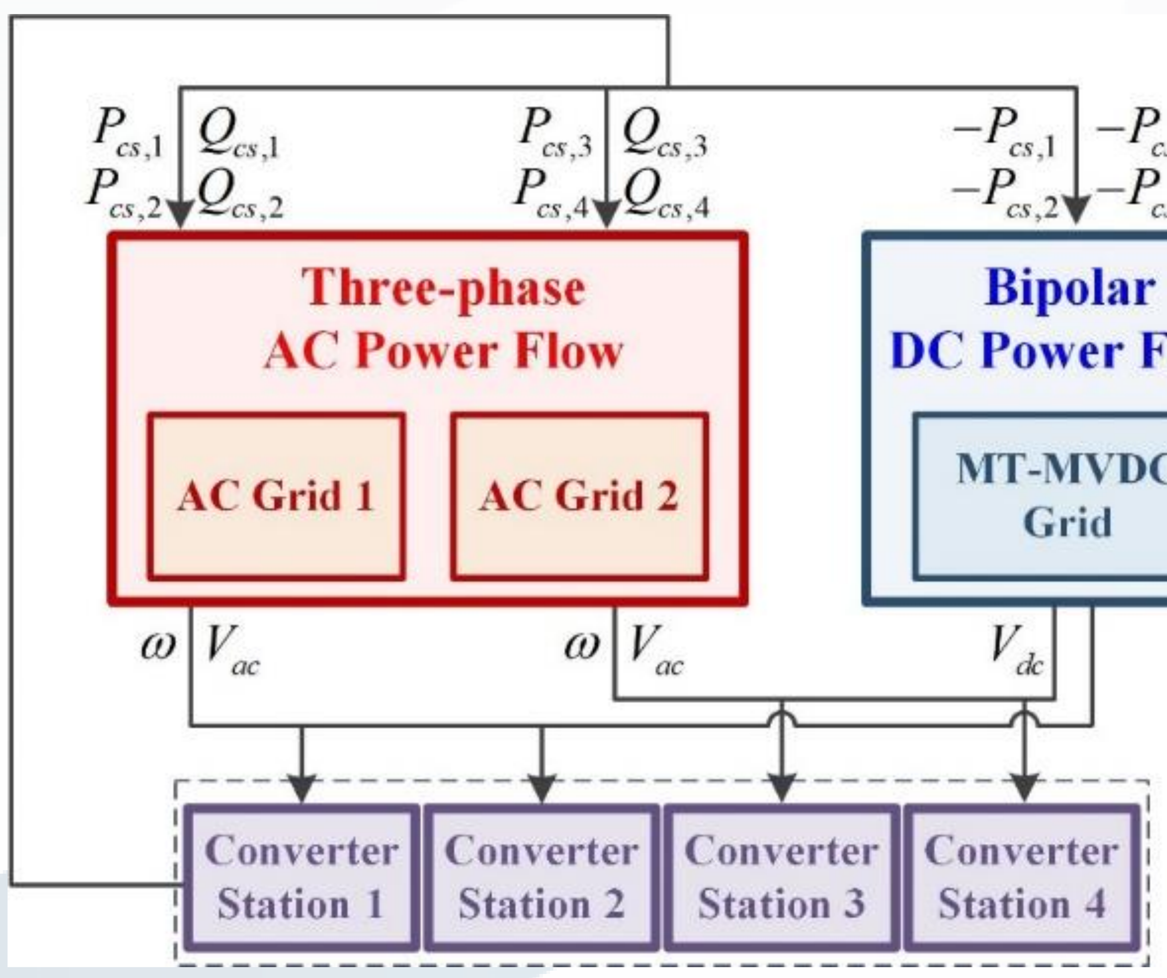
- Internal loss [AC Voltage Support]

$$P_{CS,ac} + P_{CS,dc} + P_{CS,loss} = 0$$

$$\text{where, } P_{CS,loss} = a_{CS} I_{CS}^2 + b_{CS}\left|I_{CS}\right| + c_{CS}$$

Sequential Power Flow Algorithm

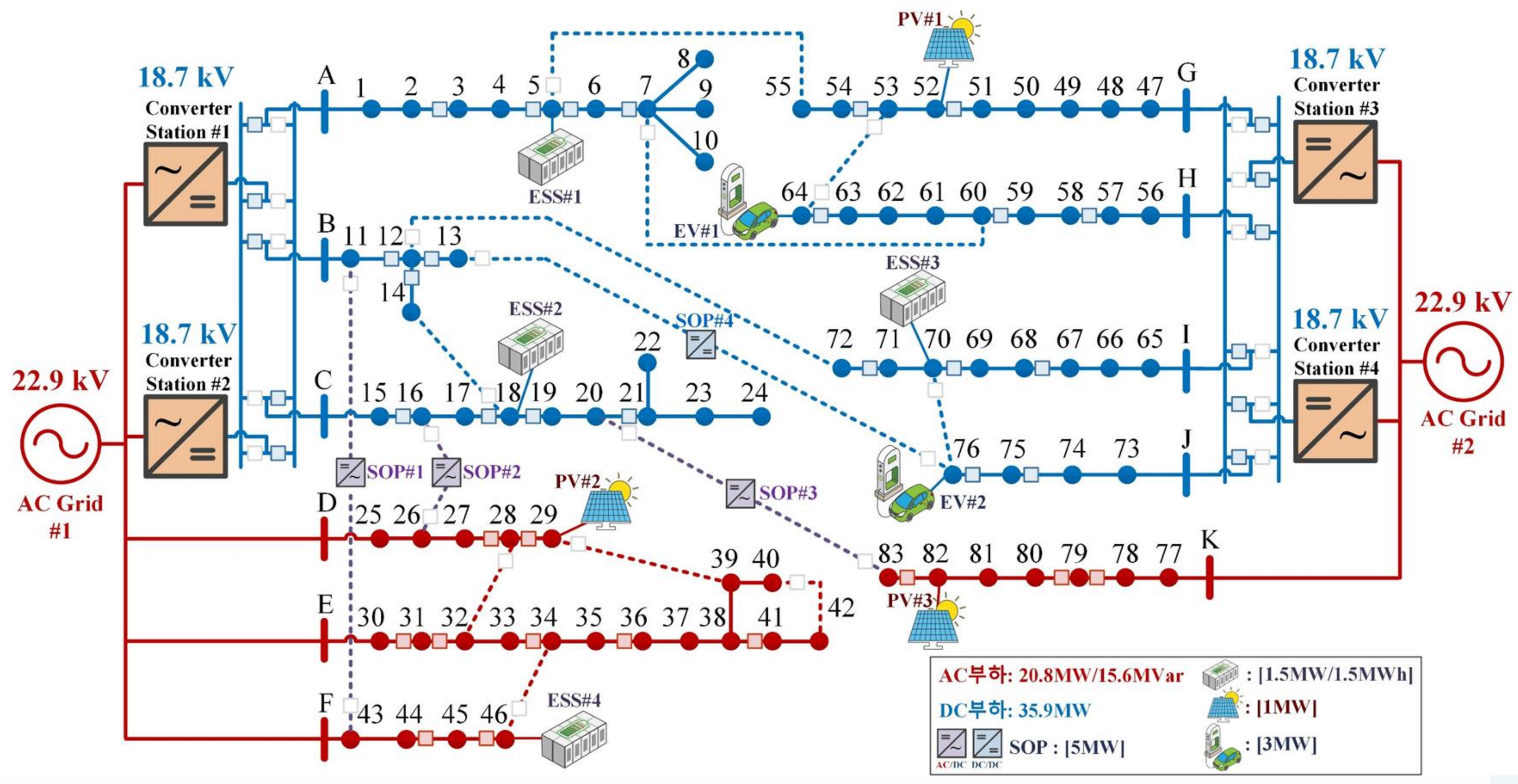
✔ AC & DC power flow algorithms are conducted separately until power flows through converter stations converge.



Case Study

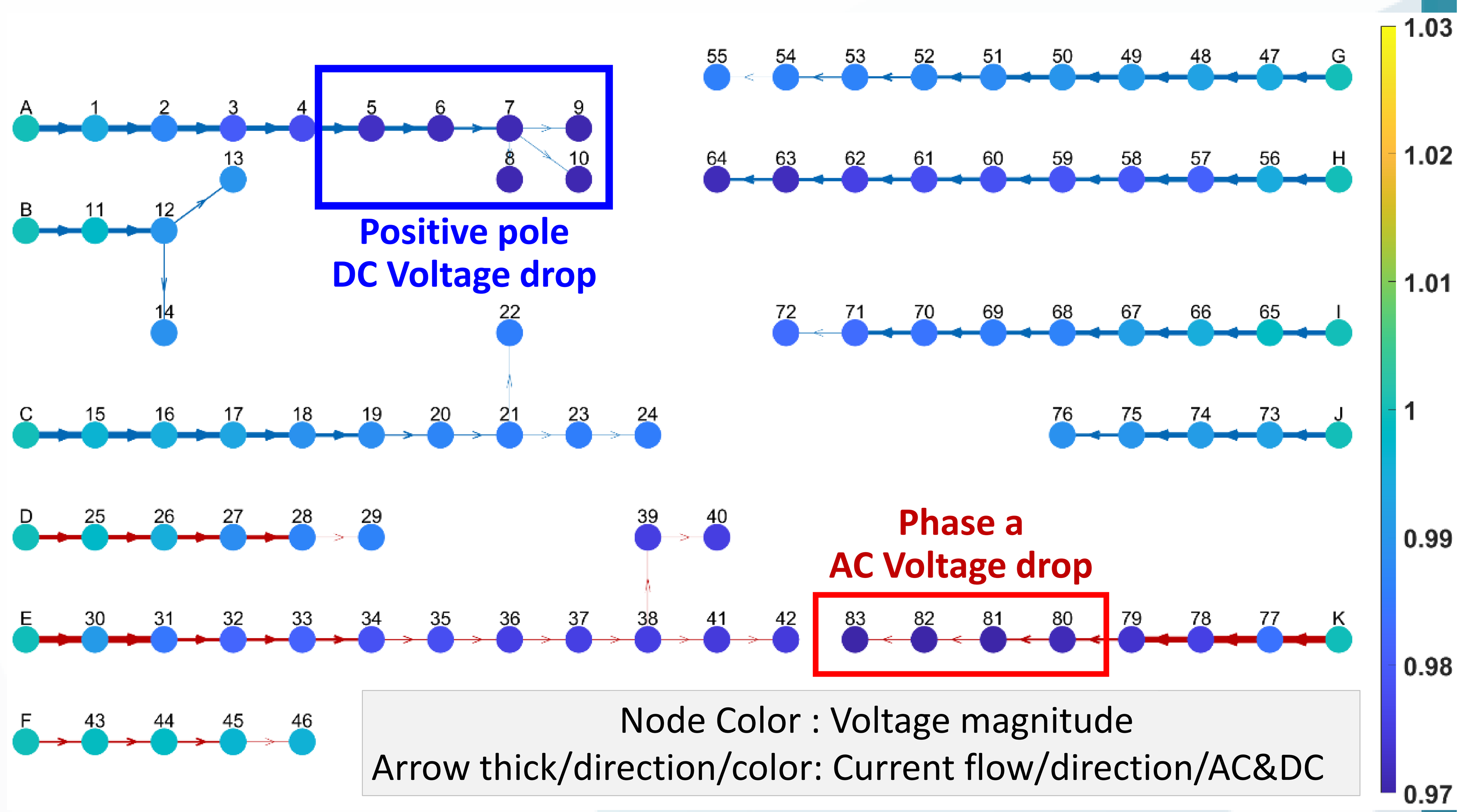
✔ Fictitious test system with four converter stations

- AC network: phase a/b/c/ loading 44/33/22%
- DC network: positive/negative loading 60/40%



✔ Power flow results – AC: phase a / DC: positive pole

- AC phase b/c and DC negative pole voltages are within safe range.



Conclusion

✔ Unbalance condition of AC & DC networks are fully considered without single-line approximation.

✔ Steady-state unbalanced voltage and current of AC&DC networks are visualized.

Additional Reading

J.-O. Lee, **"Current Injection Power Flow Analysis and Optimal Generation Dispatch for Bipolar DC Microgrids"**, IEEE Trans. Smart Grid, 2021

J.-O. Lee, **"Generic Power Flow Algorithm for Bipolar DC Microgrids based on Newton-Raphson Method"**, International Journal of Electrical Power & Energy System, 2022

J.-O. Lee, **"Power Flow Analysis of Multi-Terminal Medium Voltage Bipolar DC Distribution Networks"**, 27th International Conference on Electricity Distribution, 2023.

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