Generic Power Flow Algorithm and Optimal Power Flow for Bipolar DC Microgrids

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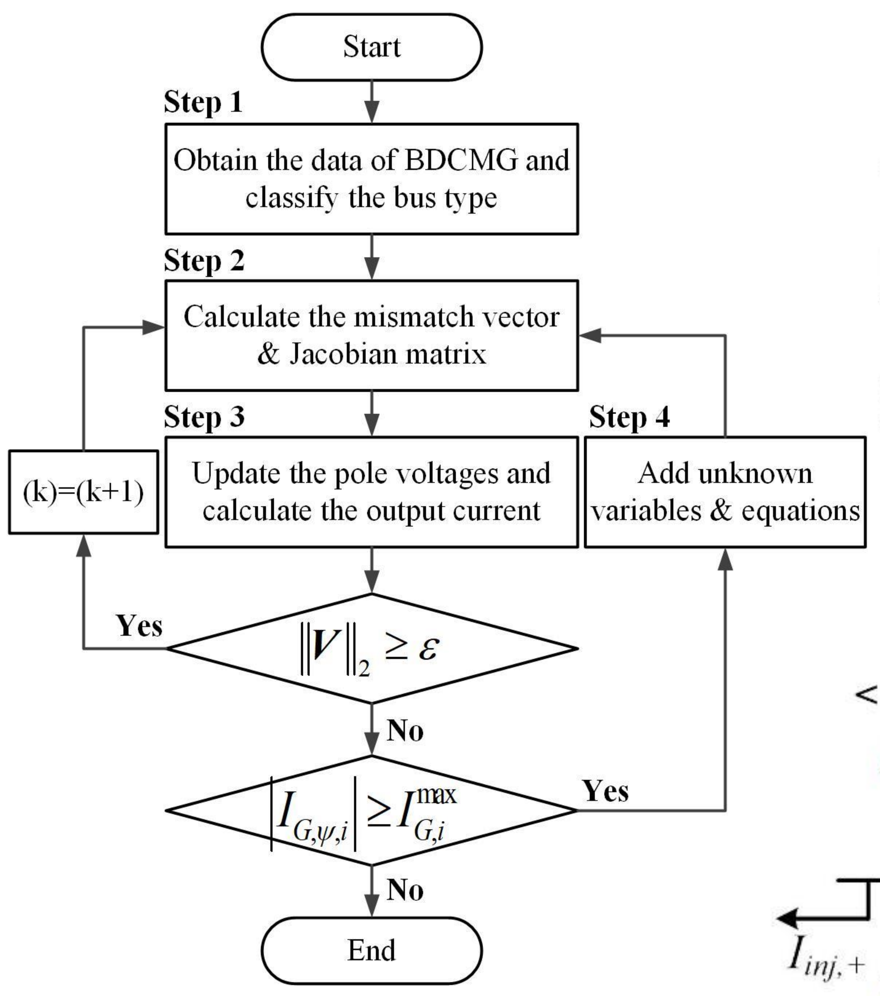
Abstract

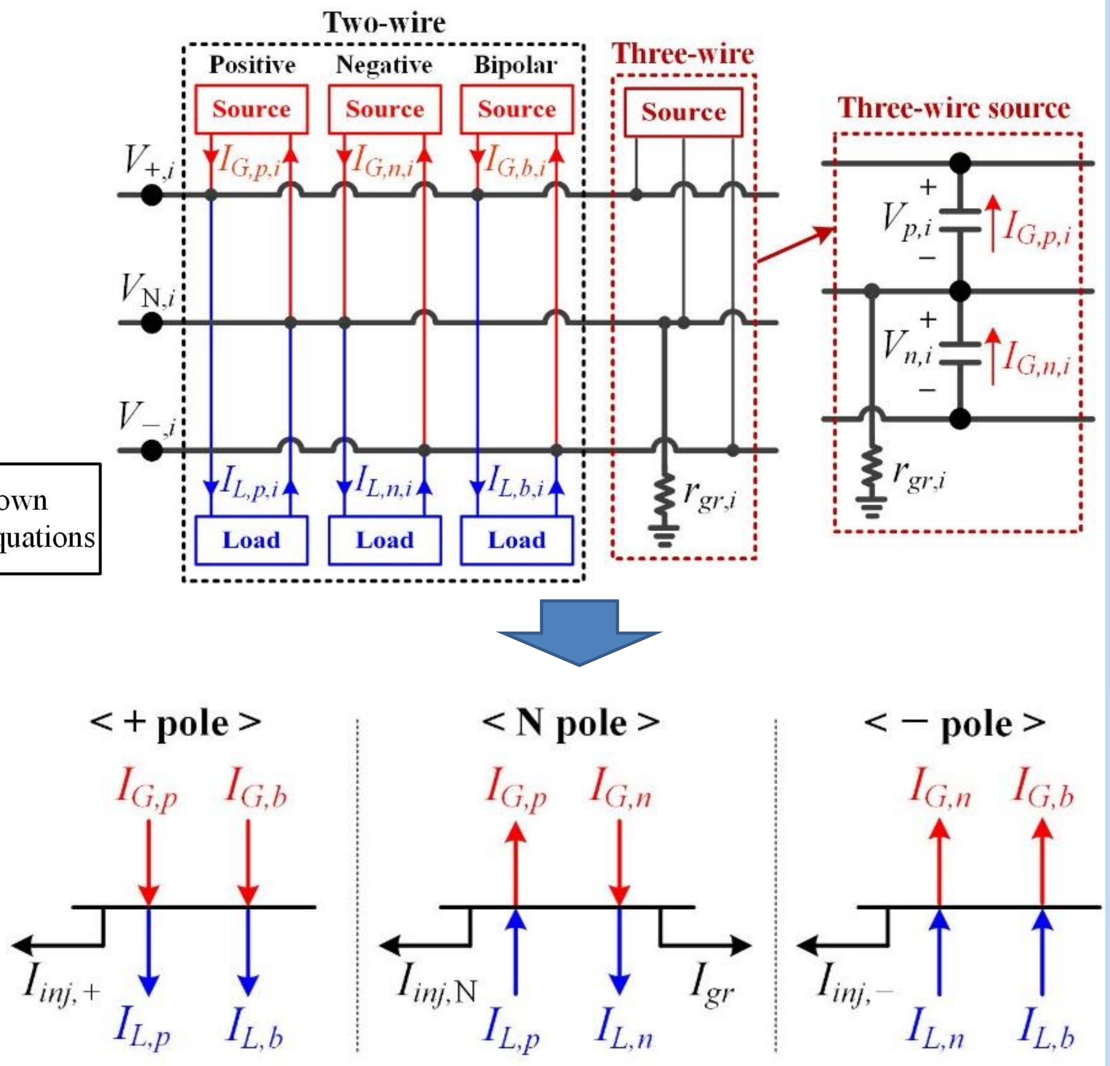
Direct current microgrids (DCMGs) have been developed as part of the ongoing transition to future power systems with the improvement of power electronics technology. Compared to unipolar structure, a bipolar structure has additional neutral conductor, thereby providing several advantages with regard to efficiency and reliability. However, single-line diagram for steady-state analysis is valid only if the DC structure is unipolar or the positive and negative connection in bipolar DCMGs is balanced. Thus, a generic power flow algorithm for bipolar DCMGs without single-line approximation is developed based on Newton-Raphson method. The developed power flow algorithm is extended to the optimal power flow (OPF) by utilizing the power flow equations as equality constraints. Therefore, the developed power flow algorithm and OPF can be helpful for economic and reliable operation of future bipolar DCMGs.

Power Flow Algorithm

- Power flow equations based on Kirchoff's current law (KCL) of each pole
- Newton-Raphson method solving nonlinear power flow equations



[Flow chart of power flow algorithm]



[Current flows of +, N, - poles]

Mathematical Model of Bipolar DC Microgrids

- Steady-state mathematical model with respect to DC voltage and current

1) Bipolar DC Network

$$I_{inj,\varphi} = G_\varphi V_\varphi,$$

2) Grounding Scheme

$$I_{gr} = diag(1/r_{gr})V_{\mathrm{N}},$$

3) Distributed Generation (DG)

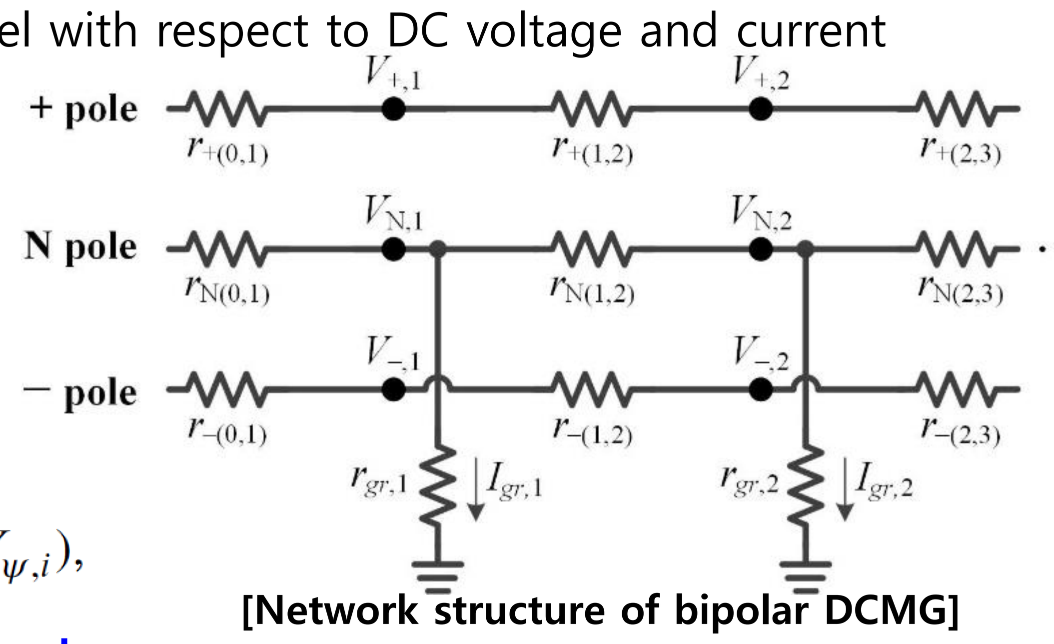
$$I_{G,\psi,i} = I^0_{G,\psi,i} + k_{G,\psi,i}(V^0_{\psi,i} - V_{\psi,i}),$$

4) Voltage Balancer (VB)

$$V_{p,i} = V_{n,i},$$

5) Load

$$I_{L,\psi,i} = I^n_{L,\psi,i}\left[z_{\psi,i}\frac{V_{\psi,i}}{V^n_\psi} + i_{\psi,i} + p_{\psi,i}\frac{V^n_\psi}{V_{\psi,i}}\right]$$



[Network structure of bipolar DCMG]

Optimal Power Flow

- Optimization problem formulation based on power flow equations
- Multiobjective with weight factors depending on priority of system operator
- Quadratic objective and linear/quadratic (in)equality constraints

min

$$f_c = P^{\mathrm{T}}_{VB}diag(a_{VB})P_{VB} + b^{\mathrm{T}}_{VB}P_{VB} + c^{\mathrm{T}}_{VB}1 + \sum_\psi P^{\mathrm{T}}_{G,\psi}diag(a_{G,\psi})P_{G,\psi} + b^{\mathrm{T}}_{G,\psi}P_{G,\psi} + c^{\mathrm{T}}_{G,\psi}1,$$ — Generation cost of DG and VB

$$f_u = \|V_p - V_n\|_2^2,$$ — Voltage unbalance of bipolar network

$$f_l = \sum_\varphi V^{\mathrm{T}}_\varphi G_\varphi V_\varphi + \sum_{i\in B_U} V^2_{\mathrm{N},i}/r_{gr,i}.$$ — Branch and ground loss

subject to

$$I_{inj,+} - (I_{G,p} + I_{G,b}) + (I_{L,p} + I_{L,b}) = 0,$$
$$I_{inj,\mathrm{N}} + I_{gr} - (-I_{G,p} + I_{G,n}) + (-I_{L,p} + I_{L,n}) = 0,$$
$$I_{inj,-} - (-I_{G,n} - I_{G,b}) + (-I_{L,n} - I_{L,b}) = 0.$$
— Current injection power flow equation (KCL)

$$-I^{line,\max}_{\varphi(i,j)} \le \frac{V_{\varphi,i} - V_{\varphi,j}}{r_{\varphi(i,j)}} \le I^{line,\max}_{\varphi(i,j)},$$ — Branch current flow limit

$$V^{\min}_\psi \le V_{p,i} \le V^{\max}_\psi,$$ — Voltage limits of positive connection

$$V^{\min}_\psi \le V_{n,i} \le V^{\max}_\psi,$$ — Voltage limits of negative connection

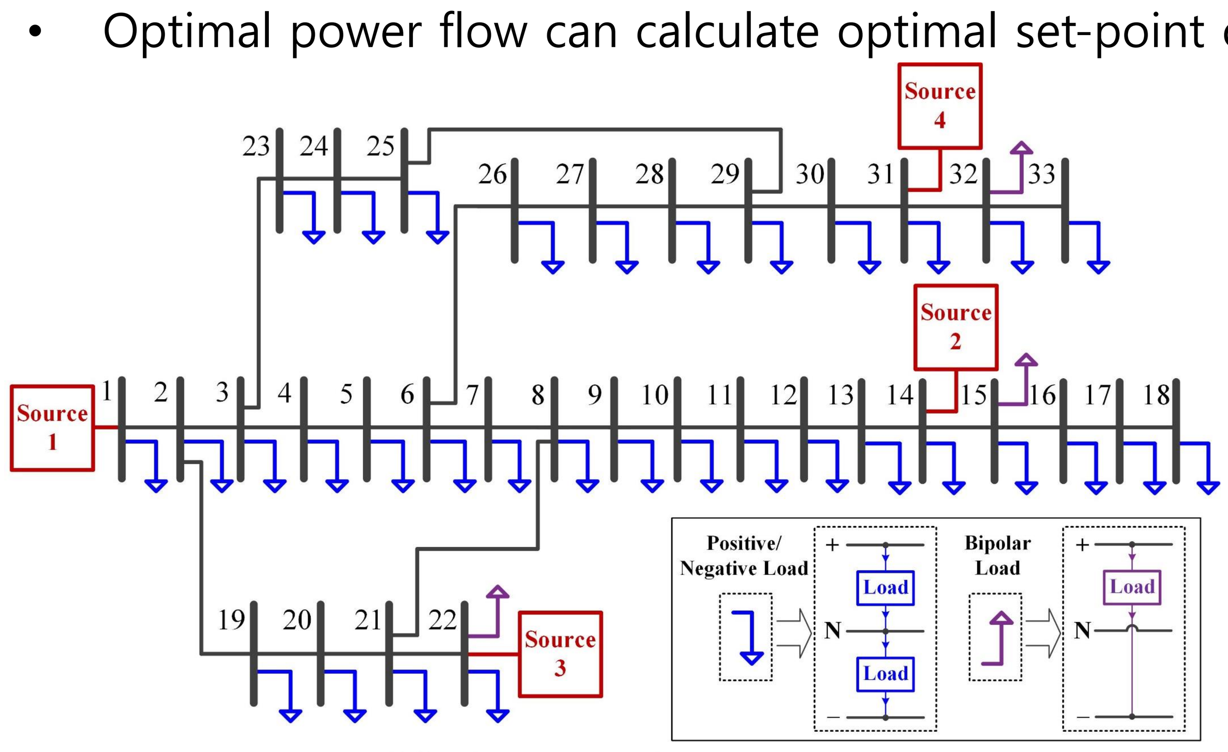
$$V_{+,i} - V_{\mathrm{N},i} = V_{\mathrm{N},i} - V_{-,i},$$ — Voltage balancing of VB

$$V_{\mathrm{N},i} = 0,$$ — Zero neutral voltage of solidly grounded

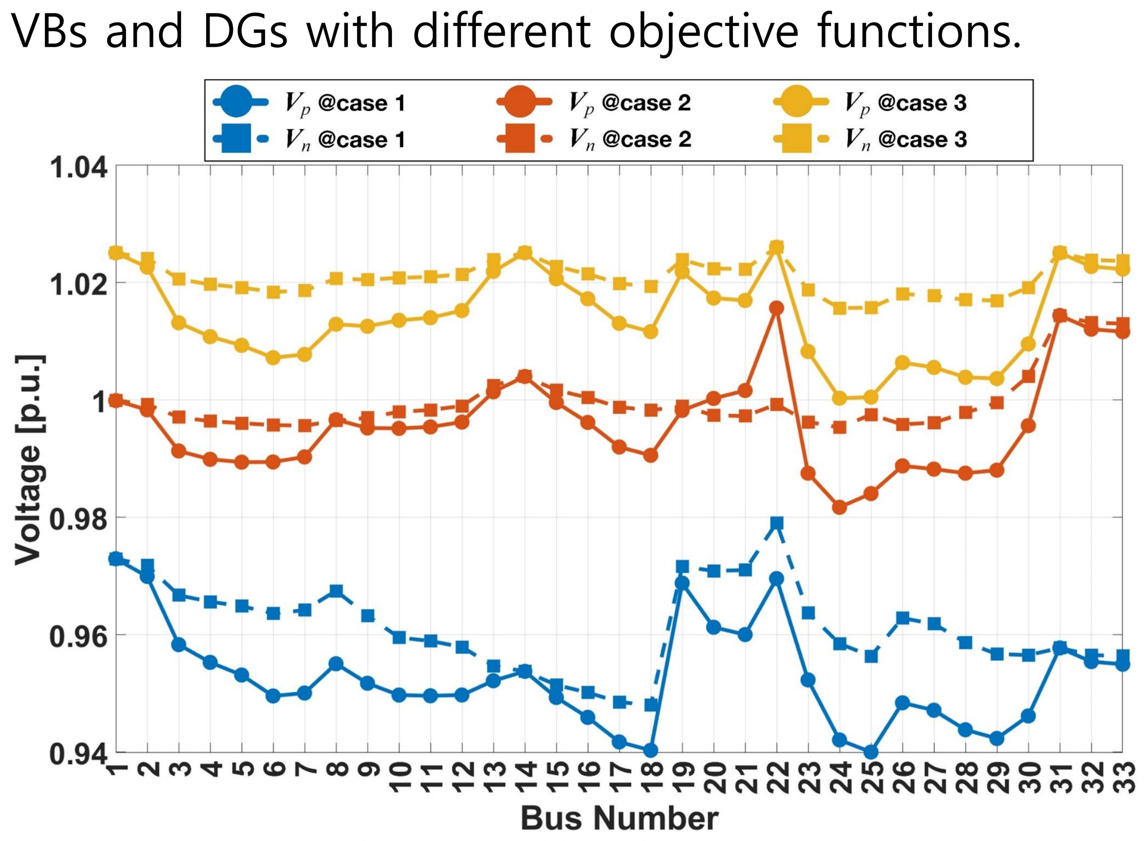
$$I^{\min}_{G,\psi} \le I_{G,\psi} \le I^{\max}_{G,\psi}.$$ — Output current limits of DG

Case Study

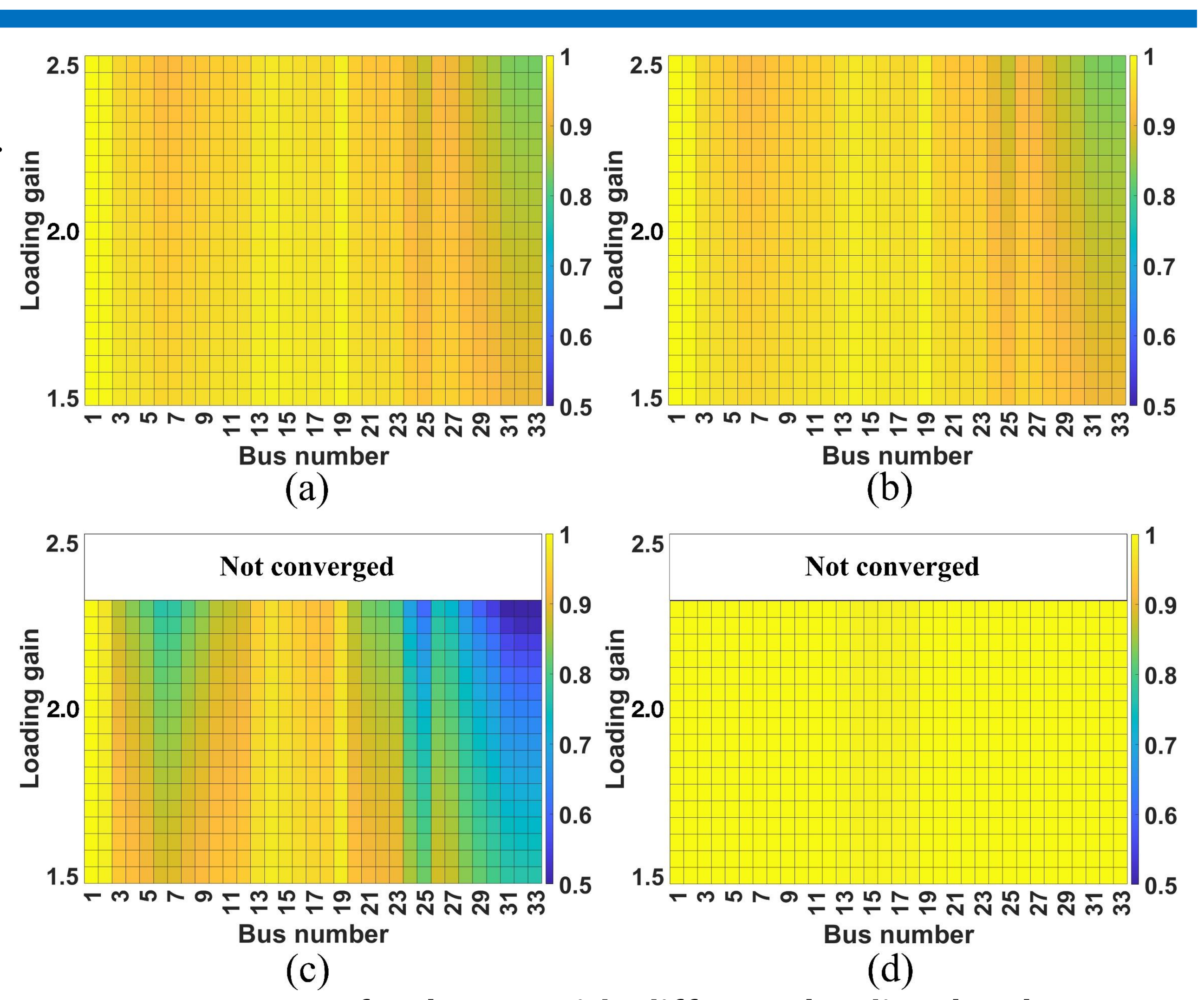
- Modified IEEE 33-bus system with multiple VBs and DGs is used to verify the proposed algorithms.
- Power flow algorithm can find steady-state operating point with high accuracy compared to PSCAD/EMTDC.
- Optimal power flow can calculate optimal set-point of VBs and DGs with different objective functions.



[Modified IEEE-33 bus test system]



[Bus voltage profile of IEEE-33 system]

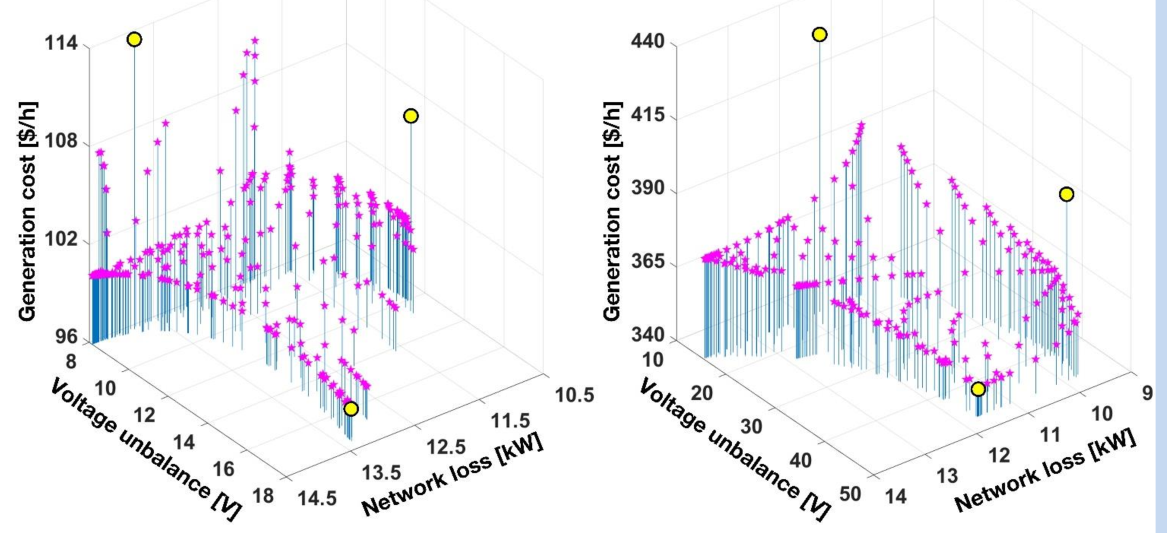


[Heatmap of voltages with different loading level]
(a) V_p at balanced (b) V_n at balanced (c) V_p at unbalanced (d) V_n at unbalanced

Allowable voltage and current bounds

Unbalance [%]	Constraint violation: Voltage $V_{p,25}$ [p.u.]	Constraint violation: Line current $I_{+(3,23)}$ [p.u.]
0	0.94	0.10
10	0.9375	0.1032
20	0.9352	0.1062
30	0.9330	0.1089
40	0.9311	0.1114
50	0.9293	0.1137

Violation



[3-D Pareto front of multiobjective OPF]

Conclusions

A power flow algorithm and OPF for bipolar DCMGs without network approximation were developed considering multiple VBs, DGs, and loads. The results show that the steady-state unknown variables and optimal operating point can be calculated with low computational burden, so the proposed algorithms can be fundamental tools for bipolar DCMGs.

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, "**Optimal Power Flow for Bipolar DC Microgrids**", International Journal of Electrical Power & Energy System, 2022