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Frequency-Reactive Power Optimization Strategy of Grid-forming Offshore Wind Farm Using DRU-HVDC Transmission

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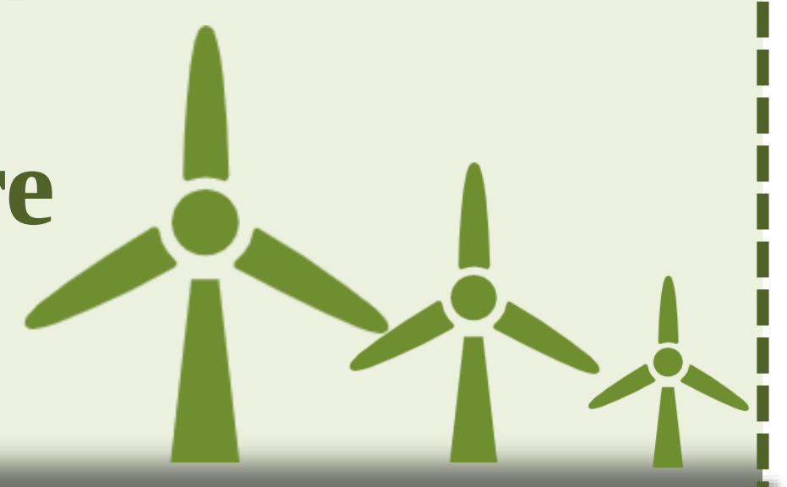
INTRODUCTION

- The diode rectifier unit-based high voltage direct current *(DRU-HVDC)* transmission with *grid-forming (GFM) wind turbine* is becoming a promising scheme for offshore wind farm(OWF) integration due to its *high reliability and low cost*



Offshore AC System

Black Start Power

GFM control is proposed for wind turbines

establish the offshore AC system

Black Start Power

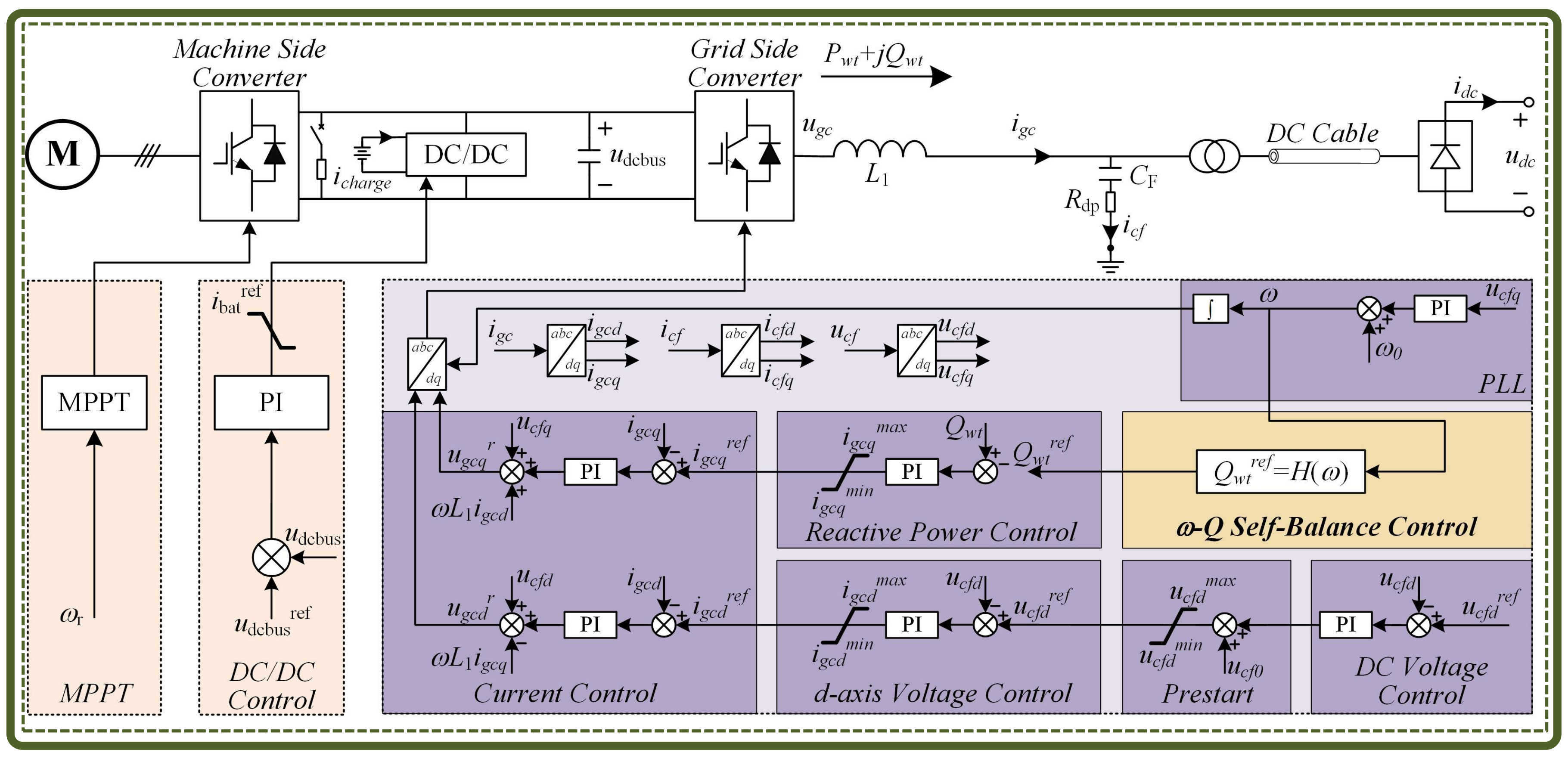
energy storage devices are installed in some wind turbines

- Currently, research on *the optimization of the reactive power flow* in such an AC system is scarce. Existing optimization analyses are mostly based on *the MMC-HVDC system and grid-following (GFL) wind farms*

- Currently, research on *the optimization of the reactive power flow* in such an AC system is scarce. Existing optimization analyses are mostly based on *the MMC-HVDC system and grid-following (GFL) wind farms*

- In the DRU-HVDC system with GFM WTs, *the reactive power flow, reactive power constraints, and reactive power distribution* are much more complex, a comprehensive system power flow modeling is carried out in this paper. *the optimal power flow (OPF)* analysis is completed, and *an optimization strategy* is proposed for WTs.

CONTROL STRUCTURE OVERVIEW



MODELING OF OPF BASED ON FREQUENCY-REACTIVE POWER CHARACTERISTICS

Basic Optimal Flow Model

$$\min_{S_i^g, V_i(\forall i\in N)} \sum_{\substack{i\in N\\ k=1,2}} c_{ki}\left(\Re\left(S_i^g\right)\right)^2 + c_{0i}$$

$$s.t.\ \underline{V} \le |V_i| \le \overline{V},\quad \forall i\in N$$

$$\underline{S}_i^g \le S_i^g \le \overline{S}_i^g,\quad \forall i\in N$$

$$|S_{ij}| \le \overline{S}_{ij},\quad \forall (i,j)\in E^+\cup E^-$$

$$S_i^g - S_i^d = \sum_{(i,j)\in E^+\cup E^-} S_{ij},\quad \forall i\in N$$

$$S_{ij} = Y_{ij}^* V_i V_i^* - Y_{ij}^* V_i V_j^*,\quad \forall (i,j)\in E^+\cup E^-$$

Optimal Power Flow Model Considering Frequency-Reactive Power Characteristics of OWF Integration

$$\begin{cases} Q_{wt\_all}(\omega) = Q_{farm}(P_{farm},\omega) \\ Q_{farm} = Q_{cf\_all} + Q_{tf\_all} + Q_{net} + Q_{DR} \end{cases}$$

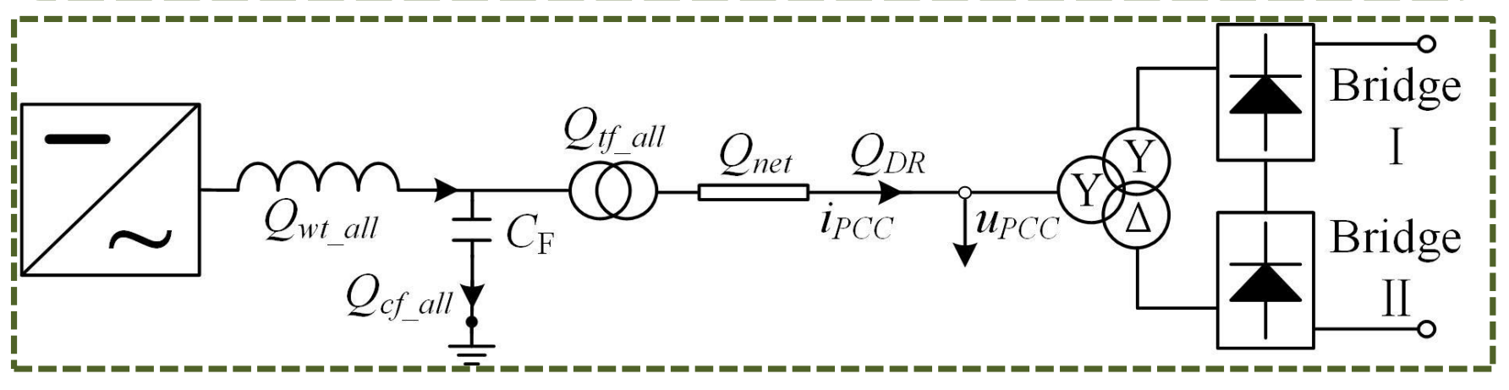
$$Q_{DR} = P_{farm}\tan(\varphi)$$

$$\varphi = \arctan\left(\frac{2\mu - \sin(2\mu)}{1-\cos(2\mu)}\right)$$

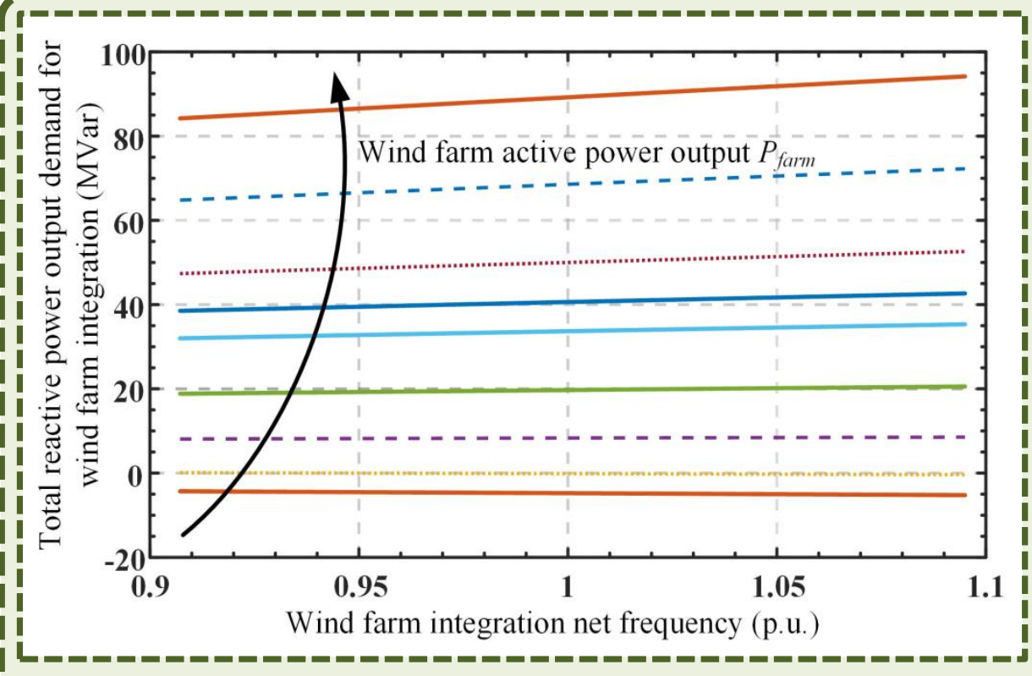
$$\begin{cases} Q_{net} = 1.5 i_{pcc}^2 \omega L_{net} - 1.5 u_{pcc}^2 \omega C_{net} \\ i_{pcc} = P_{farm}/1.5 u_{pcc}\cos(\varphi) \end{cases}$$

$$Q_{cf\_all} = -1.5\left(u_{pcc}/n_{tf}\right)^2 N_{\omega t}\omega C_F$$

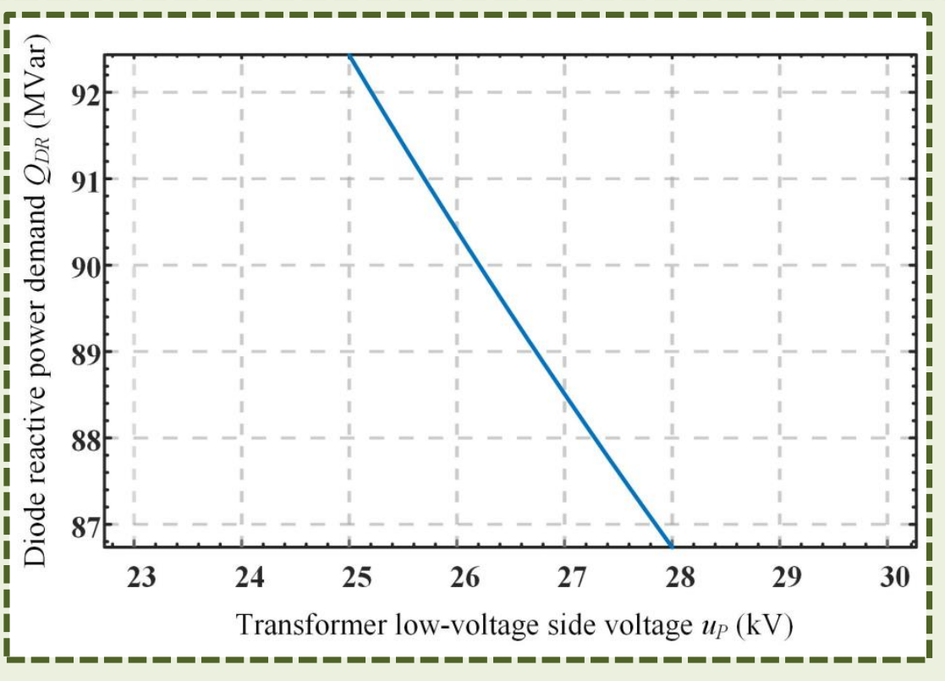
$$Q_{tf\_all} = 1.5 N_{\omega t}\left(i_{pcc} n_{tf}/N_{\omega t}\right)\omega L_{tf}$$



Reactive power distribution diagram of OWF



Static operation point of wind farm frequency



Nonlinear reactive power flow Characteristics introduced by DR

$$Q_{\omega t\_all}(\omega, P_1, P_2, \ldots\ldots, P_k) = k_1\left(\sum P_i\right)^2\omega + k_2\omega + k_3\sum P_i$$

Numerically linear form

$$Q_{\omega t\_all}(\omega) = d_1\omega + d_2$$

RELAXATION

$$V_i V_j^* = W_{ij},\quad i,j\in N$$

$$\underline{V}^2 \le W_{ii} \le \overline{V}^2,\quad \forall i\in N$$

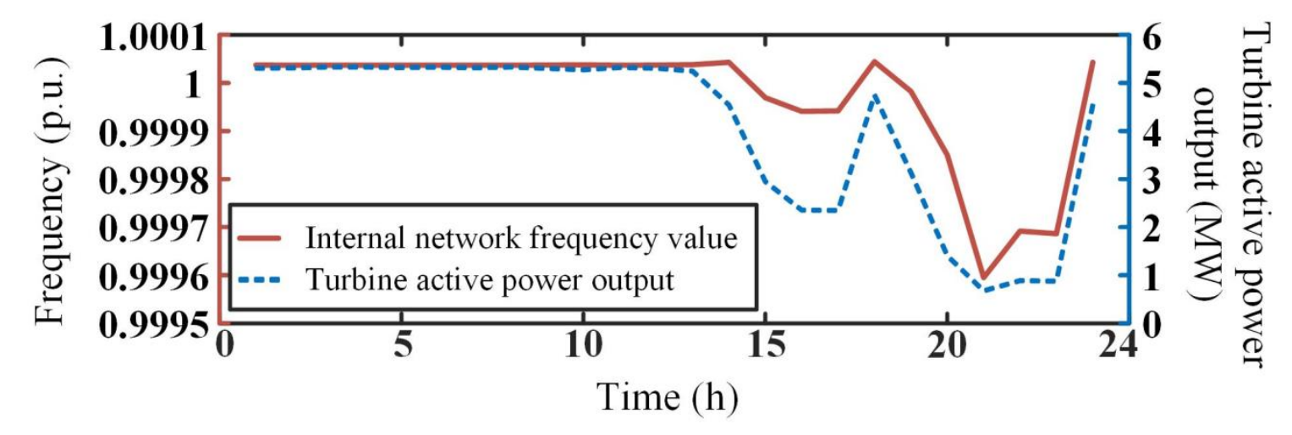
$$S_{ij} = Y_{ij}^* W_{ii} - Y_{ij}^* W_{ij},\quad \forall (i,j)\in E^+\cup E^-$$

$$\left\| \begin{matrix} 2W_{ij} \\ W_{ii} - W_{jj} \end{matrix} \right\| \le W_{ii} + W_{jj}$$

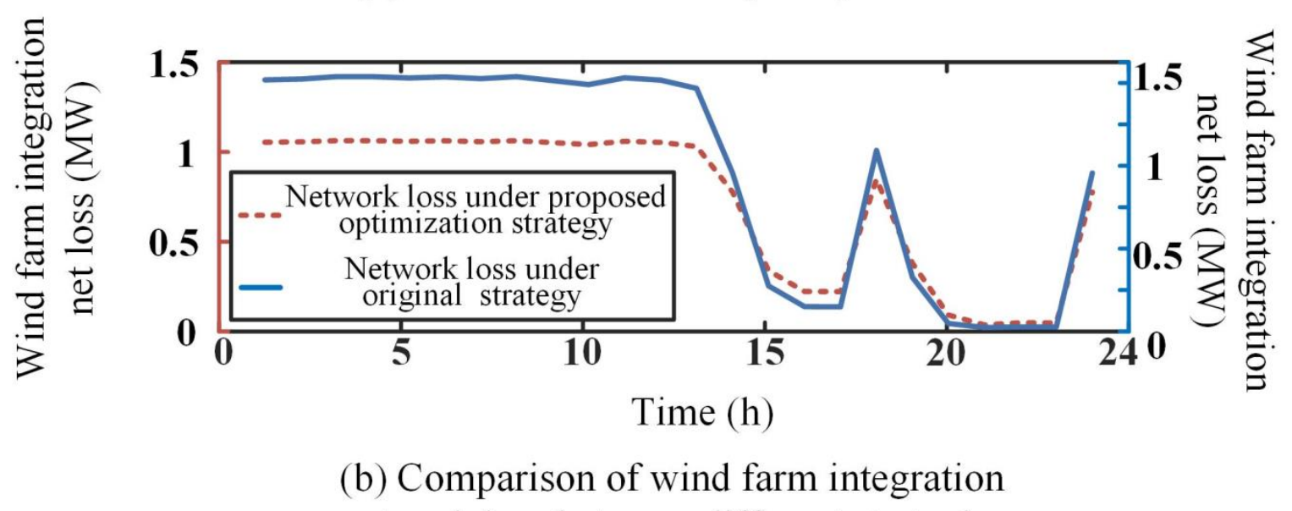
- The *SDP relaxation* involves the abandonment of the challenging *non-convex constraint of rank(W)=1* in the model, thereby relaxing the OPF problem into an *SDP programming problem*.

- To further simplify this problem, considering *the semi-definite equivalence conditions for W regarding principal minors*, ignoring the inequalities involving principal minor of the third order and above, yields a specific class of SDP relaxation known as *second-order cone programming (SOCP) relaxation*.

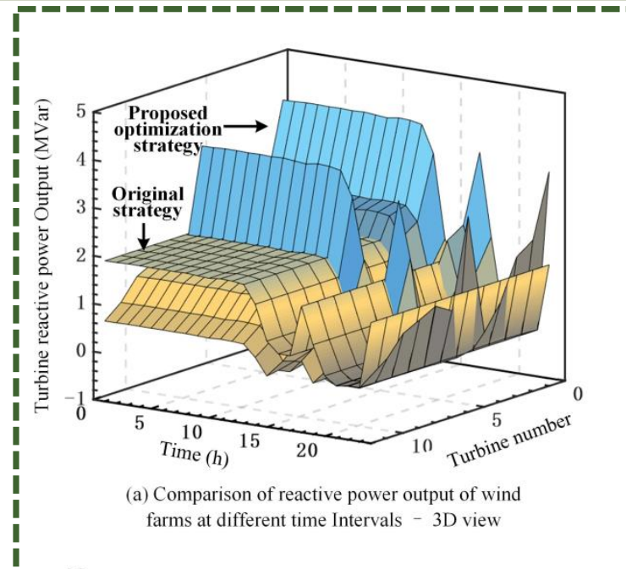
RESULT AND CONCLUSION



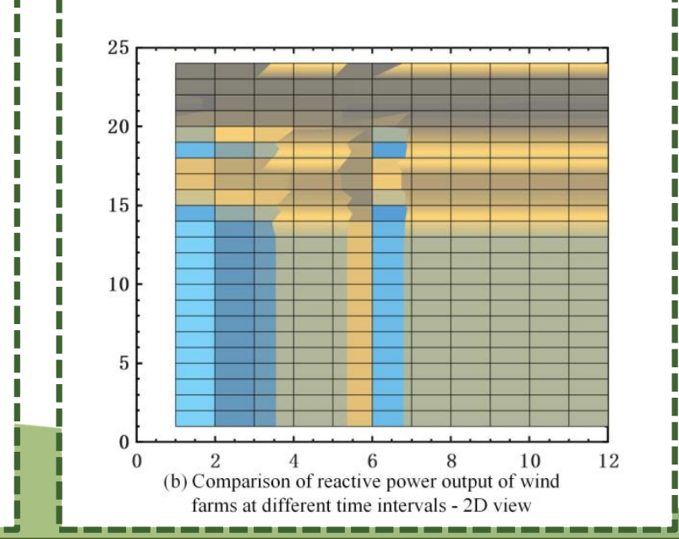
(a) Internal network frequency value



(b) Comparison of wind farm integration network loss between different strategies



(a) Comparison of reactive power output of wind farms at different time Intervals – 3D view



(b) Comparison of reactive power output of wind farms at different time intervals - 2D view

- A detailed model is established for power flow analysis and optimization.
- Improved optimization constraints, including reactive power demand and frequency stability, are considered.
- A frequency-reactive power optimization control strategy is conducted by adjusting the reactive power output of each wind turbine and the internal network frequency
- The simulation results shows that the proposed optimization strategy can effectively reduce network losses for the offshore AC system. This effect is particularly significant when the active power output of WTs is relatively high (50% to 70% load capacity), with an optimization ratio of network losses exceeding 25.3%.