Adaptive Parametric Impedance Model Order Reduction Method for Grid-tied Renewable Energy Dominated Microgrid

Xun Jiang[1], Meiqin Mao[1], Liuchen Chang[2]

1. Hefei University of Technology, 2. University of New Brunswick

Abstract - The high-precision reduced order impedance model can significantly reduce the computation burden in the small-signal oscillatory instability detection process of grid-tied renewable energy dominated microgrids (REMGs). However, due to improper interpolation strategies, the existing model order reduction method cannot build the high-precision parametric reduced order impedance model (PROIM) for REMG. To fill these gaps, this paper proposes the adaptive parametric model order reduction method to build a high-precision PROIM for REMGs. In this method, the adaptive optimization of system parameters and frequency interpolation points is achieved by introducing the evaluation indexes including convergence error, cumulative error, and projection matrix rank. The error performance of the obtained PROIM by the proposed method and its efficiency in actual oscillatory stability analysis are validated by a small-scale REMG with 4 different converter-based renewable generators (CREGs) and a real-time simulation model using a large-scale REMG of 4.2 MW with 18 different CREGs.

1 Full-Order Impedance Model of the Investigated REMG

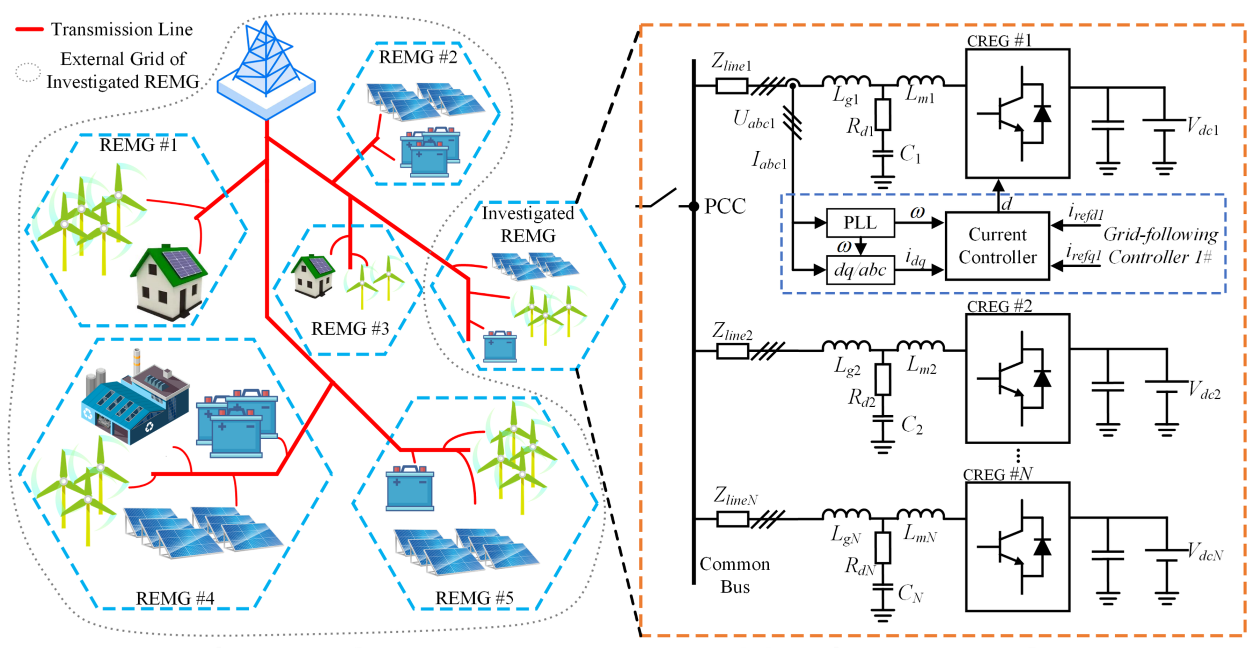


Fig. 1. Topology of power system with clusters of REMGs

$$\begin{cases}\begin{pmatrix}\dot{\boldsymbol{x}}_1\\ \vdots\\ \dot{\boldsymbol{x}}_i\end{pmatrix}=\begin{pmatrix}\boldsymbol{A}_{\mathrm{GFI},1} & 0 & 0\\ 0 & \ddots & 0\\ 0 & 0 & \boldsymbol{A}_{\mathrm{GFI},i}\end{pmatrix}\begin{pmatrix}\boldsymbol{x}_1\\ \vdots\\ \boldsymbol{x}_i\end{pmatrix}+\begin{pmatrix}\boldsymbol{B}_{\mathrm{GFI},1}\\ \vdots\\ \boldsymbol{B}_{\mathrm{GFI},i}\end{pmatrix}\begin{pmatrix}\boldsymbol{u}_1\\ \vdots\\ \boldsymbol{u}_i\end{pmatrix}\\ y=\left(\boldsymbol{C}_{\mathrm{GFI},1}\ \cdots\ \boldsymbol{C}_{\mathrm{GFI},N}\right)\left(\boldsymbol{x}_1\ \cdots\ \boldsymbol{x}_i\right)^{\mathrm{T}}\end{cases}$$

$$Z_{\mathrm{MCFS}}(s)=1/\left(\boldsymbol{C}_{\mathrm{MCFS}}\left(s\boldsymbol{I}-\boldsymbol{A}_{\mathrm{MCFS}}\right)^{-1}\boldsymbol{B}_{\mathrm{MCFS}}\right)$$

2 Proposed AP-IMOR Method

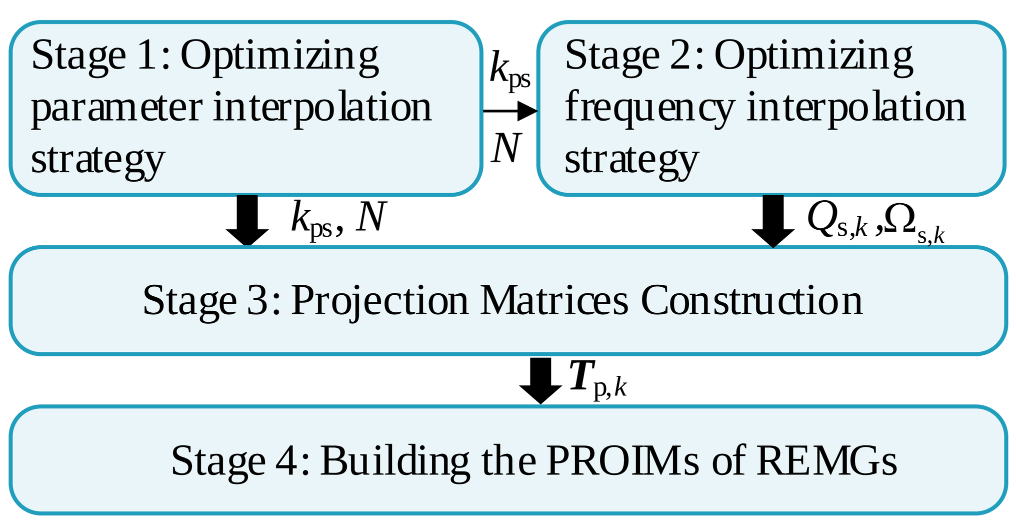


Fig. 2. Proposed AP-IMOR Method

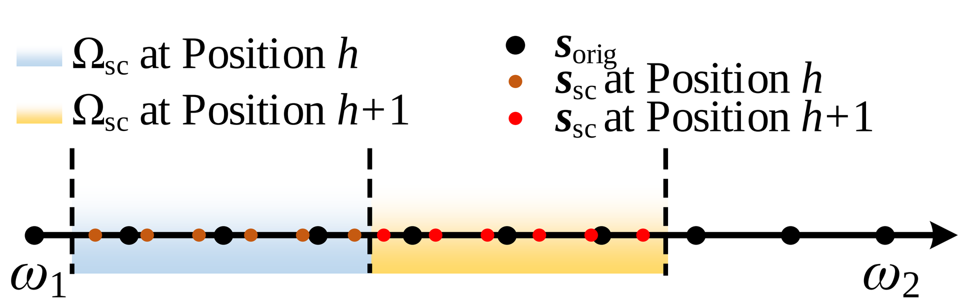
- **Stage 1: Parameter Interpolation Optimization**

$\boldsymbol{X}(s_i)$ solving process should meet the cumulative error constraint Th_{err} and convergence error Th_{conv} constraints

$$\begin{cases}\min\limits_{\boldsymbol{X}_k(s_i)}\sum\limits_{j=1}^{N}\left\|(s_i\boldsymbol{E}(\lambda_j)-\boldsymbol{A}(\lambda_j))\boldsymbol{X}_k(s_i)-\boldsymbol{B}(\lambda_j)\right\|_F^2\\ \text{s.t.}\quad \boldsymbol{X}_k(s_i)\in\mathrm{C}^{n\times1}\qquad 1\le k\le k_{ps}\\ \qquad \max(\boldsymbol{E}_{\mathrm{C}}(s_i))\le \mathrm{Th}_{\mathrm{conv}}\\ \qquad \max(\boldsymbol{X}_{\mathrm{err}}(s_i))<\mathrm{Th}_{\mathrm{err}}\end{cases}$$

- **Stage 2: Frequency Interpolation Optimization**

Maximizing the rank of $\boldsymbol{T}_{\mathrm{p}}$ with minimum frequency interpolation points



$$\begin{cases}\max\ rank(\boldsymbol{T}_{\mathrm{p}})=rank(\mathrm{span}\{\boldsymbol{X}(\boldsymbol{s}_{\mathrm{sub}}),\boldsymbol{X}(\boldsymbol{s}_{\mathrm{res}})\})\\ \text{s.t.}\quad Q=\min(Q_T)\\ \qquad \boldsymbol{s}_{\mathrm{sub}}\in\Omega_{\mathrm{sub}},\boldsymbol{s}_{\mathrm{res}}\in\Omega_{\mathrm{res}}\end{cases}$$

- **Stage 3: Projection Matrices Construction**

$$(s_i\boldsymbol{E}(p)-\boldsymbol{A}(p))\boldsymbol{X}(s_i)=\boldsymbol{B}(p)\qquad X(s_i)=\left(\sum_{j=1}^{M}\boldsymbol{M}_i(\lambda_j)^{\mathrm{H}}\boldsymbol{M}_i(\lambda_j)\right)^{-1}\times\sum_{j=1}^{M}\boldsymbol{M}_i(\lambda_j)^{\mathrm{H}}\boldsymbol{B}(\lambda_j)$$

$$\boldsymbol{T}_{\mathrm{p}}\supseteq\mathrm{span}\{\boldsymbol{X}(s_1),\boldsymbol{X}(s_2),\cdots,\boldsymbol{X}(s_i)\}$$

- **Stage 4: Building PROIM**

$$\begin{cases}\boldsymbol{E}(p)\dot{\boldsymbol{x}}=\boldsymbol{A}(p)\boldsymbol{x}+\boldsymbol{B}(p)u\\ y=\boldsymbol{C}(p)\boldsymbol{x}\end{cases}\xrightarrow{\text{Projection Matrix } \boldsymbol{T}_{\mathrm{p}}}\begin{cases}\boldsymbol{E}_r(p)\dot{\boldsymbol{x}}_r=\boldsymbol{A}_r(p)\boldsymbol{x}_r+\boldsymbol{B}_r(p)u\\ y=\boldsymbol{C}_r(p)\boldsymbol{x}_r\end{cases}$$

3 Simulation Verification and Discussion

3.1 Error Comparision of Different Model Order Reduction Methods

Method 1 is the traditional KS-PMOR without interpolation optimizing, Method 2 and Method 3 can meet part of the error constraints.

Method	Convergence Error Constraint	Cumulative Error Constraint	T_p Rank Maximum
Method 1	×	×	×
Method 2	√	×	×
Method 3	√	√	×
AP-IMOR	√	√	√

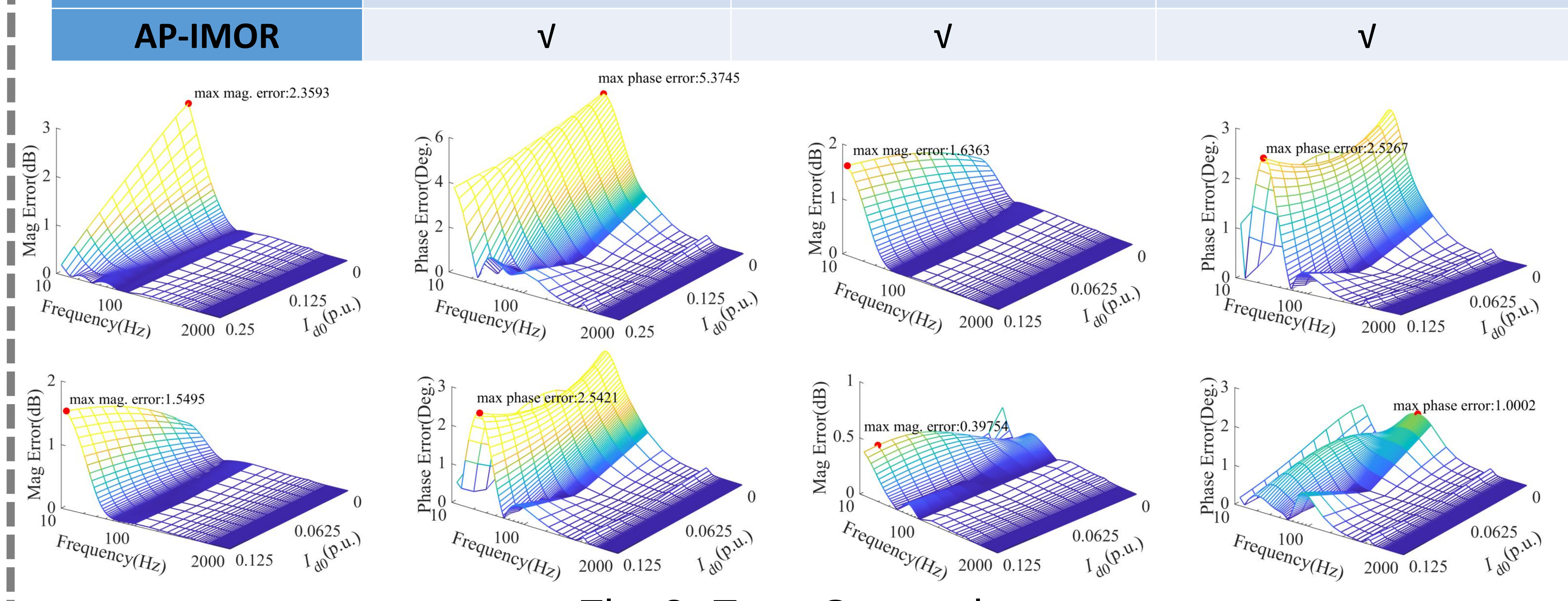


Fig. 3. Error Comparison

Compared with methods 1-3, the maximum magnitude error with Strategy 4 is reduced by 93.15%, 75.7%, and 74.34%, respectively; and the maximum phase errors are reduced by 81.4%, 60.42%, and 60.66%, respectively.

3.2 Application of the obtained PROIM to the Oscillatory Stability Analysis

- **Computational Burden Comparison**

	Time Consumption	Memory Usage
Full Order IM	49.195s	25972KB
PROIM	11.068s	616KB

The time consumption of the oscillatory stability analysis can be reduced by 77.5%, meanwhile, the memory usage can be decreased by 97.6%.

- **Stability Analysis Results**

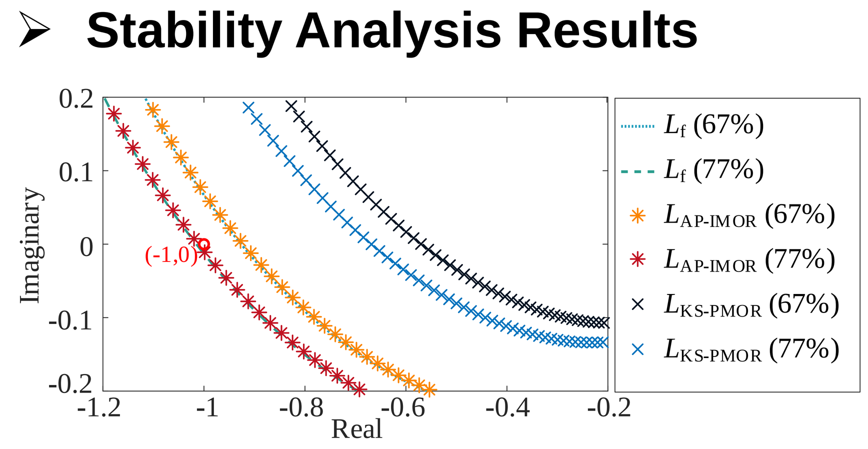


Fig. 3. Nyquist Curve with Different Model

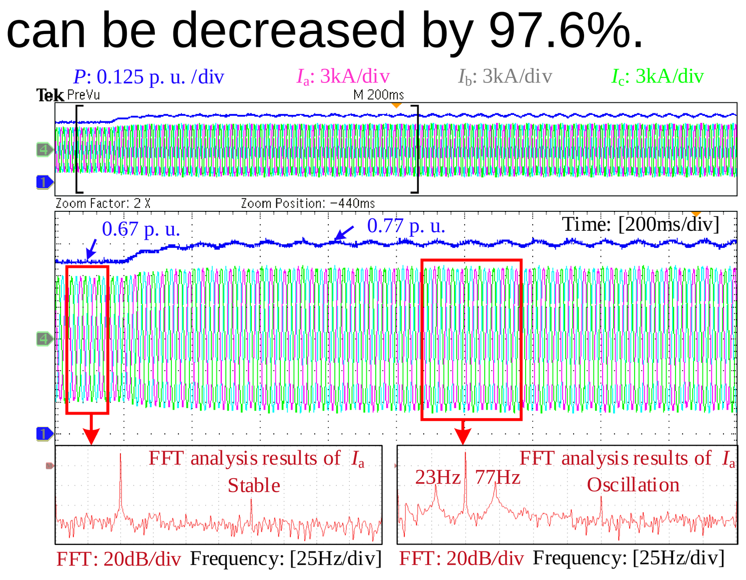


Fig. 3. Time Domain HIL Experiment Results

4.Conclusion

In this paper, the AP-IMOR method with an adaptive interpolation optimization algorithm is originally proposed as a general method to obtain the high-precision PROIM of REMGs. Simulation results indicate that the proposed method significantly enhances the accuracy of model order reduction, while achieving substantial reductions in model order. The obtained PROIM is promising for the seconds-level and minutes-level online oscillatory stability analysis in REMG. Thus, the proposed method is general and can apply to the PROIM of different REMGs such as distributed renewable energy power stations, wind farms, and alike.

合肥工業大學