The Impact of Load Models in an Algorithm for Improving Voltage Stability via Demand Response

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Introduction

This work employs **demand response** to improve voltage stability via **virtual spatial shifting** of loads. The total load is kept constant so that frequency stability is unaffected.

Proper load models are particularly important in stability studies. The load models we use in this work: **ZIP** and **Induction Machine**

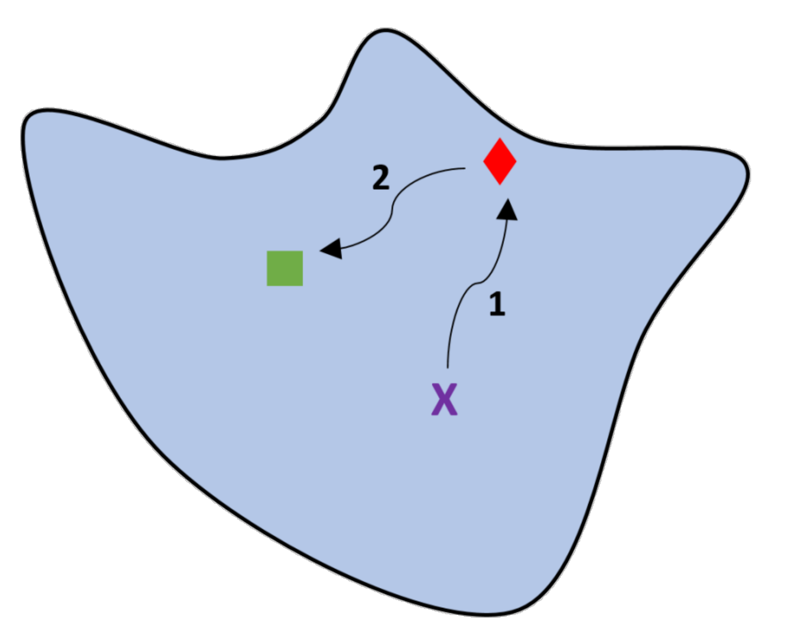


Figure 1: Conceptual description of the problem

Load Models

1. Controllable ZIP Model

$$\mathcal{F}_k^{ZP}(V_k,\varepsilon_k)=\varepsilon_k P_{d,k}^0\left[a_{1,k}\left(\frac{V_k}{V_k^0}\right)^2+a_{2,k}\left(\frac{V_k}{V_k^0}\right)+a_{3,k}\right]$$

$$\mathcal{F}_k^{ZQ}(V_k,\varepsilon_k)=\varepsilon_k Q_{d,k}^0\left[b_{1,k}\left(\frac{V_k}{V_k^0}\right)^2+b_{2,k}\left(\frac{V_k}{V_k^0}\right)+b_{3,k}\right]$$

2. Induction Machine Model

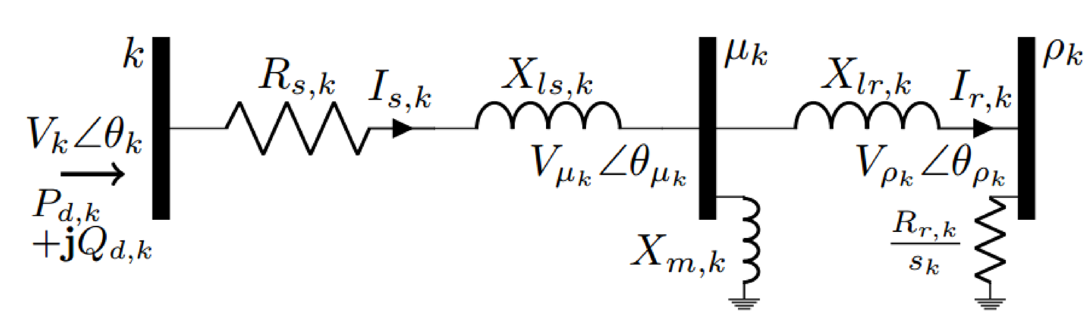


Figure 2: Steady-state equivalent circuit of a IM

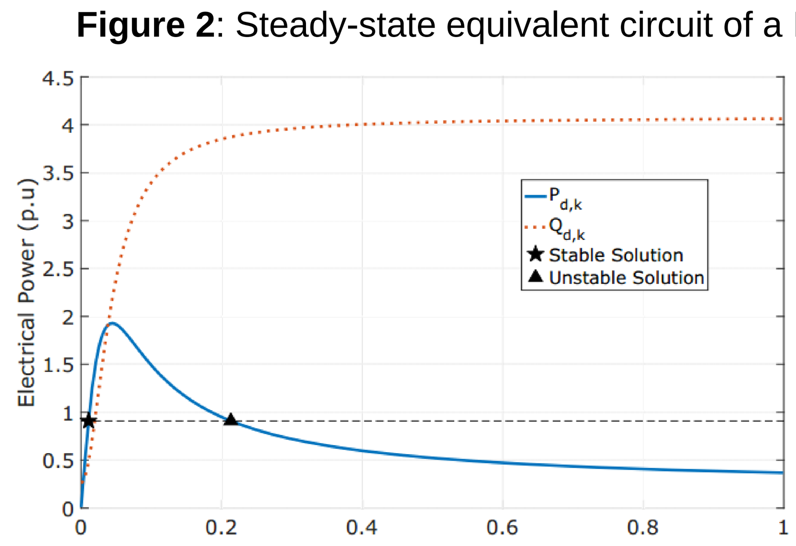


Figure 3: Power as a function of the slip

3. Composite Load Model $S_{d,k}=(1-\alpha)S_{\mathrm{ZIP},k}+\alpha S_{\mathrm{IM},k}$

Optimization Formulation

1. Jacobian matrix

$$J_{\mathrm{cnv}}=\begin{bmatrix}\frac{\partial\mathcal{F}_i^P}{\partial\theta_i} & \frac{\partial\mathcal{F}_i^P}{\partial V_j}\\ \frac{\partial\mathcal{F}_j^Q}{\partial\theta_i} & \frac{\partial\mathcal{F}_j^Q}{\partial V_j}\end{bmatrix}\qquad J_{\mathrm{ZIP}}=J_{\mathrm{cnv}}+\begin{bmatrix}\mathbf{0}_{n-1\times n-1} & \frac{\partial\mathcal{F}_i^{ZP}}{\partial V_j}\\ \mathbf{0}_{n_{\mathrm{pq}}\times n-1} & \frac{\partial\mathcal{F}_j^{ZQ}}{\partial V_j}\end{bmatrix}$$

$$J_{\mathrm{IM}}=\begin{bmatrix}J_{\mathrm{cnv}} & \mathbf{0}_{m\times 5n_{\mathrm{dr}}}\end{bmatrix}+\begin{bmatrix}\frac{\partial\mathcal{F}_i^{IP}}{\partial\theta_i} & \frac{\partial\mathcal{F}_i^{IP}}{\partial V_j} & \frac{\partial\mathcal{F}_j^{IP}}{\partial\theta_{\mu,k}} & \frac{\partial\mathcal{F}_i^{IP}}{\partial V_{\mu,k}} & \frac{\partial\mathcal{F}_i^{IP}}{\partial\theta_{\rho,k}} & \frac{\partial\mathcal{F}_i^{IP}}{\partial V_{\rho,k}} & \frac{\partial\mathcal{F}_j^{IP}}{\partial s_k}\\ \frac{\partial\mathcal{F}_j^{IQ}}{\partial\theta_i} & \frac{\partial\mathcal{F}_j^{IQ}}{\partial V_j} & \frac{\partial\mathcal{F}_j^{IQ}}{\partial\theta_{\mu,k}} & \frac{\partial\mathcal{F}_j^{IQ}}{\partial V_{\mu,k}} & \frac{\partial\mathcal{F}_j^{IQ}}{\partial\theta_{\rho,k}} & \frac{\partial\mathcal{F}_j^{IQ}}{\partial V_{\rho,k}} & \frac{\partial\mathcal{F}_j^{IQ}}{\partial s_k}\end{bmatrix}$$

$$J_{\mathrm{com}}=(1-\alpha)\begin{bmatrix}J_{\mathrm{ZIP}} & \mathbf{0}_{m\times 5n_{\mathrm{dr}}}\end{bmatrix}+\alpha J_{\mathrm{IM}}$$

2. Formulation

$$\max\quad \lambda_0$$

$$\text{subject to}\quad J_{\mathrm{com}}J_{\mathrm{com}}^T-\lambda_0 I\succeq 0$$
smallest singular value of the power flow Jacobian

$$\textstyle\sum_{i\in\mathcal{S}_{\mathrm{DR}}}P_{d,i}=P_{d,total}$$
Total flexible demand is constant

$$\mathcal{F}(x)=0$$
AC power flow equations, Generator P, V are fixed

$$\mathcal{G}(x)\geq 0$$
Operational limits

$$x=\{P_g,Q_g,V,\theta,V_\mu,\theta_\mu,V_\rho,\theta_\rho,s,\varepsilon\}$$

3. Solution approach: **Iterative linear programming**

Results

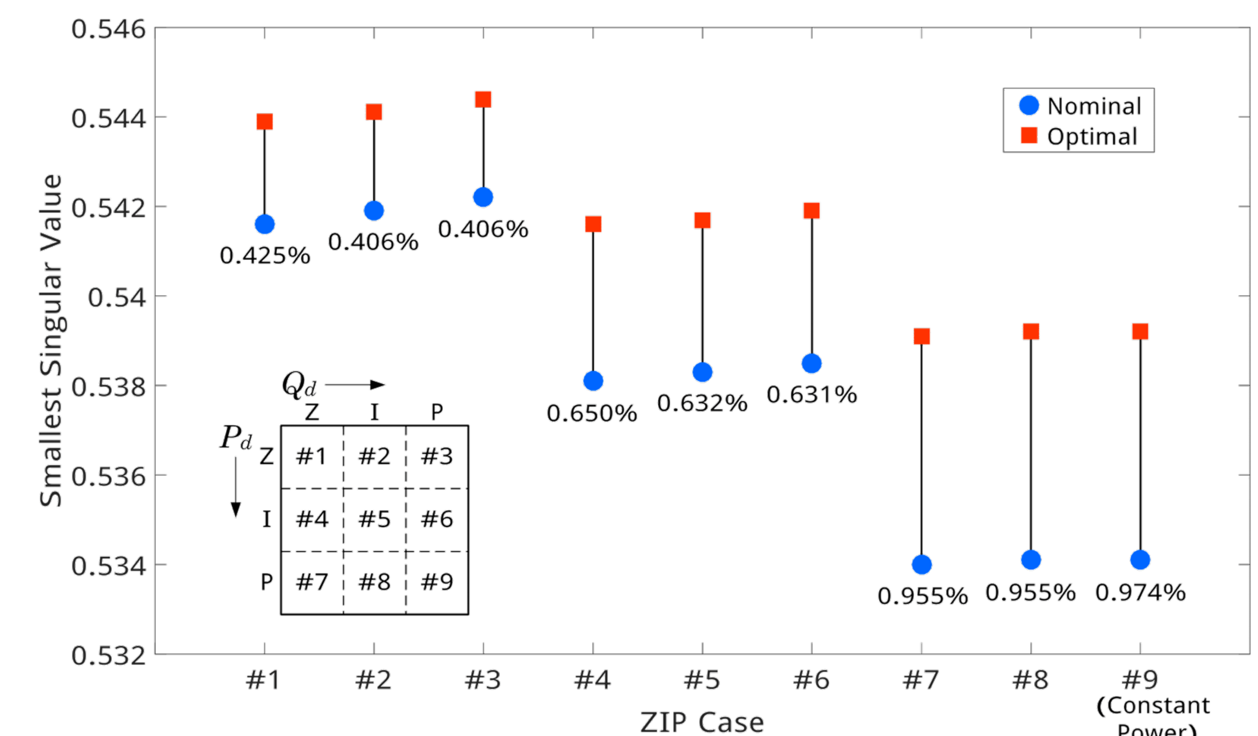


Figure 4: The nominal and optimal SSV for different ZIP cases

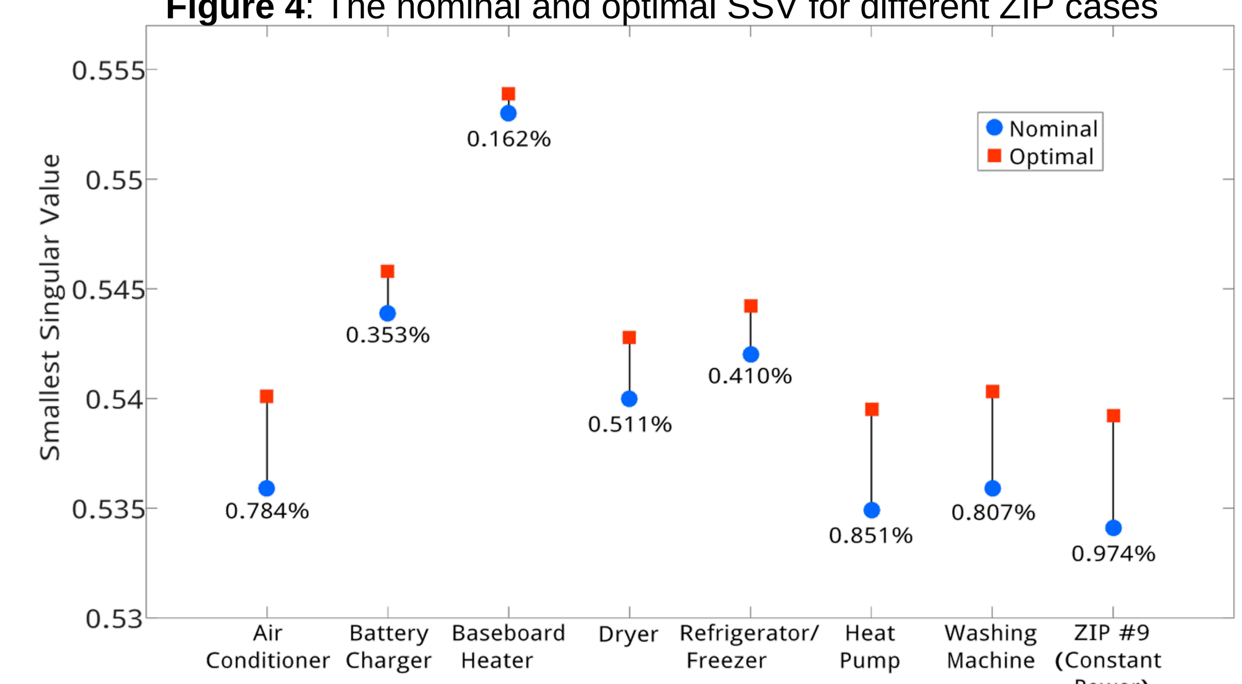
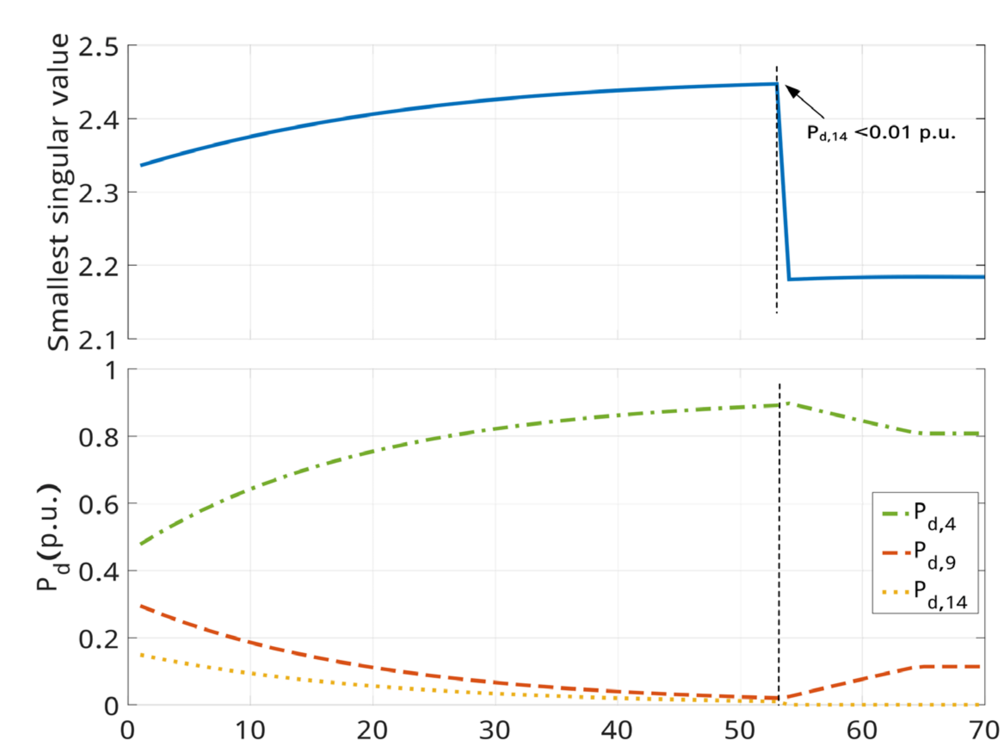


Figure 5: The nominal and optimal SSV for common DR



IM at Bus 14 ON

	P_d	Q_d
Bus 4	90.99	48.90
Bus 9	0.62	15.55
Bus 14	0.59	15.79
SSV	2.4533	

IM at Bus 14 OFF

	P_d	Q_d
Bus 4	80.81	43.94
Bus 9	11.39	17.51
Bus 14	-	-
SSV	2.184	

Figure 6: Convergence of SSV and real power demand of the DR if IM at bus 14 is disconnected at low loading

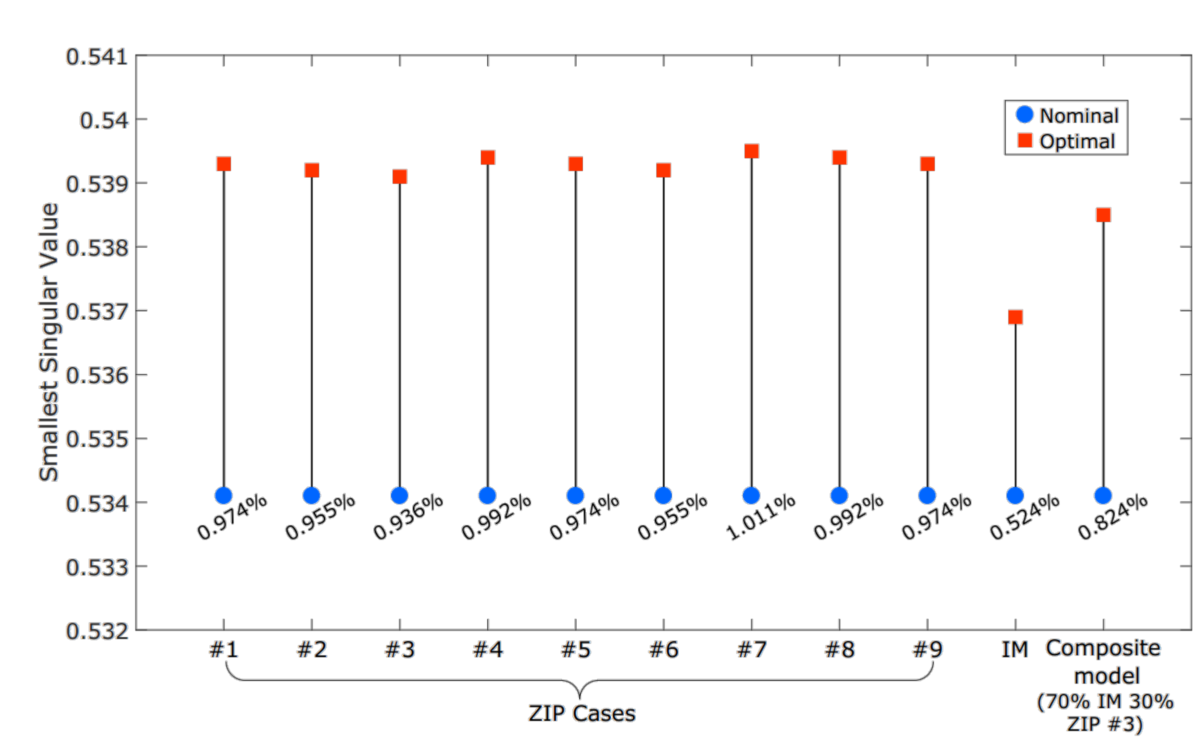


Figure 7: The nominal and optimal SSV of conventional Jacobian matrix

Table 1: Optimal loading patterns and SSV

Load Model	Nominal		Optimal for 3 DR buses									
Load Model	Constant Power		Constant Power		ZIP #3		ZIP #3		IM		IM	
Jacobian	J_{cnv}		J_{cnv}		J_{ZIP}		J_{cnv}		J_{IM}		J_{cnv}	
	P_d	Q_d	P_d	Q_d	P_d	Q_d	P_d	Q_d	P_d	Q_d	P_d	Q_d
Bus 4	47.80	32.62	92.20	62.90	92.20	63.99	92.20	63.99	90.99	48.90	71.28	39.94
Bus 9	29.50	20.73	0.00	0.00	0.00	0.00	0.00	0.00	0.62	15.55	20.34	18.50
Bus 14	14.90	16.39	0.00	0.00	0.00	0.00	0.00	0.00	0.59	15.79	0.59	15.73
SSV	0.5341		0.5393		0.5444		0.5391		2.4533		0.5369	

Acknowledgements

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