Quantifying the seismic risk for electric power distribution systems

Leo Yang Liu, Liam Wotherspoon, Nirmal Nair, Daniel Blake

Introduction

- Electric power distribution systems are generally more prone to disruption from natural hazards than transmission systems due to their often less redundant circuit structures
- Seismic risk assessment framework for electric power distribution systems is presented considering both the network topology and the functional vulnerability of distribution substations.
- The seismic risk is jointly quantified using multiple risk metrics, and importance measures are used to determine criticality of substation components for prioritization of seismic retrofit.
- The framework allows the quantification of different network topologies and substation configurations. This enables network owners and operators to evaluate the seismic vulnerability of their substation configuration and network topology, identify potential bottlenecks of the systems and thus inform effective planning and risk-reduction investments

Substation Modelling

- Distribution substations are the bridges between transmission and distribution networks. A typical double bus bar substation topology is shown in Fig.1, where double circuits are used for the purpose of emergency and maintenance.
- The substation design follows a typical disconnector -component- disconnector pattern: each component is placed in between disconnectors, with the disconnectors providing isolation from other components

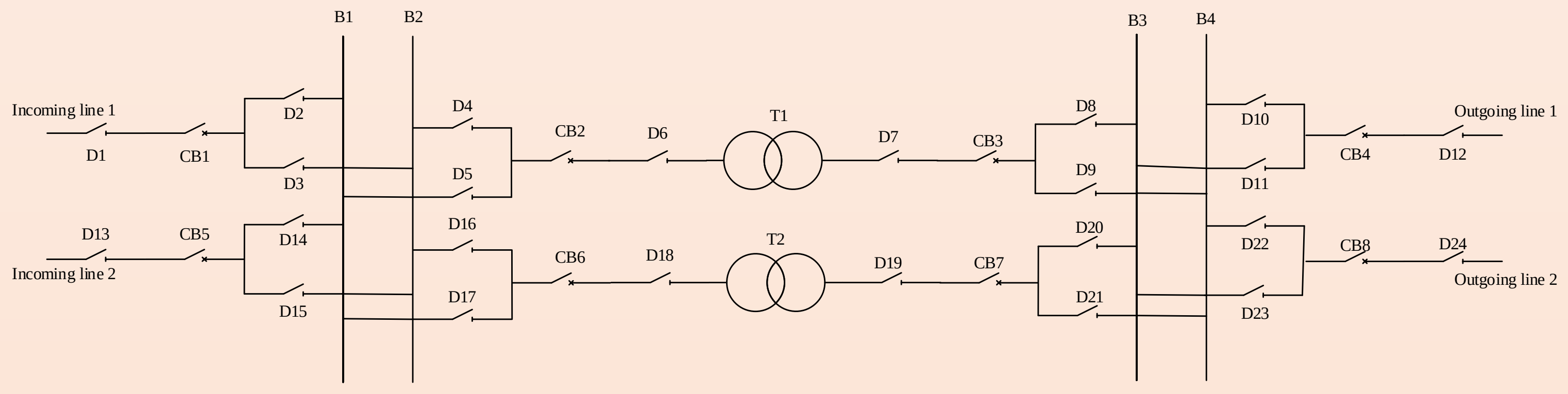


Figure 1 Typical double bus bar substation layout and the associated substation components

Distribution Network

- Modified CIGRE medium voltage test network.
- The network has a rural character and supplies a small town and the surrounding area.
- Rated voltage level 20 kV, supplied from a 110 kV transformer substation.
- The network can be operated either as weakly meshed by closing switches S1, S2 and S3 in Figure 2, or as a radial network if the switches are left open.

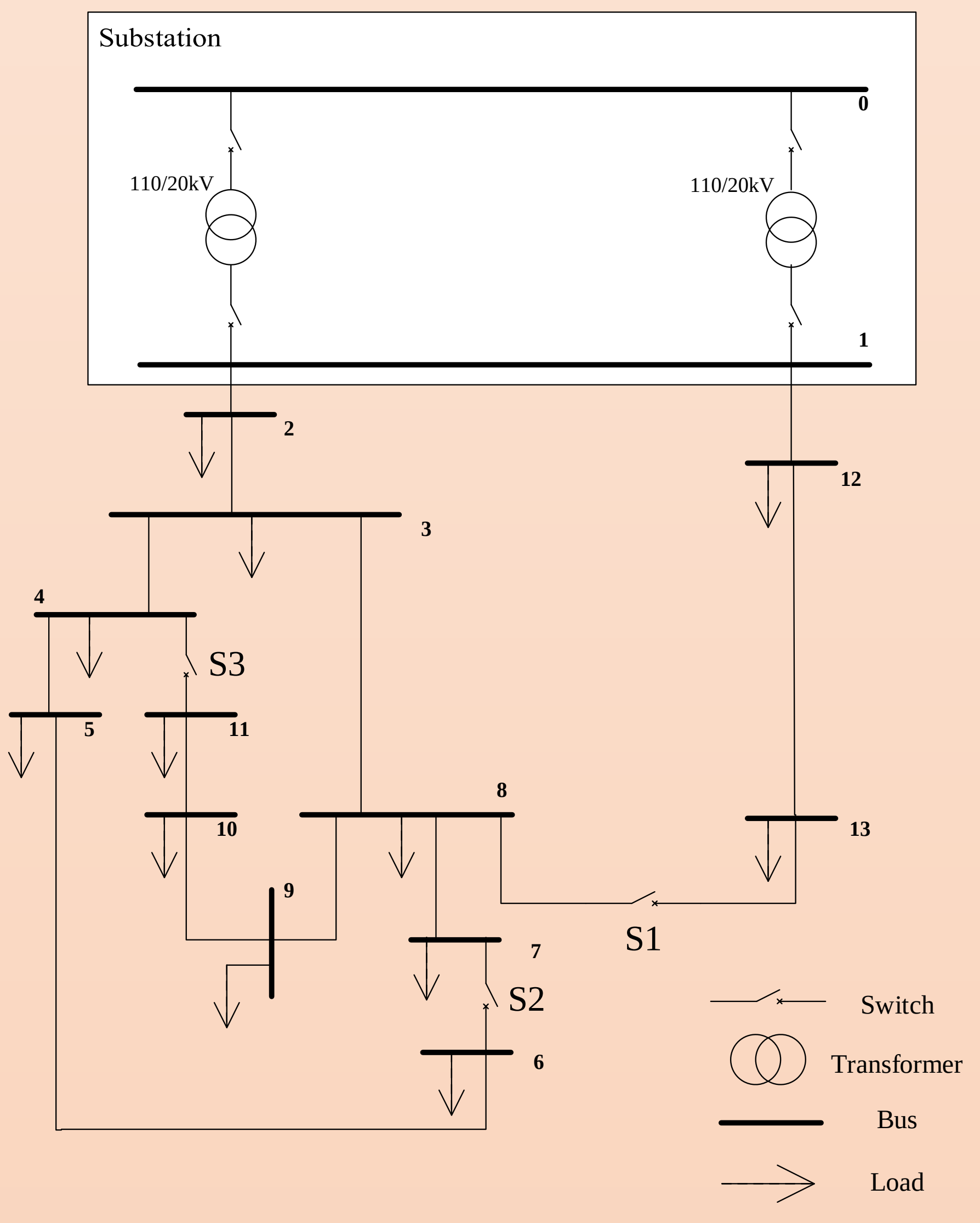


Figure 2 CIGRE medium voltage distribution test system

Power Flow Modelling

- Newton-Raphson method is conventional to solve transmission power flow. However, it is known to have convergence problems for solving distribution power flow due to the special features of distribution systems.
- Transmission networks are highly reactive i.e. low resistance to reactance ratio. This makes the Jacobian matrix diagonal dominant, facilitating computation of its inverse.
- Distribution networks are much more resistive compared with transmission networks, meaning the R/X ratio is higher. This can lead to singularity of the Jacobian matrix, forbidding the application of Newton-Raphson method.
- In order to overcome the difficulty, the implicit Z-bus method is implemented whose convergence is independent of the R/X ratio and thus is adopted as the solution algorithm for the distribution power flow.

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$$

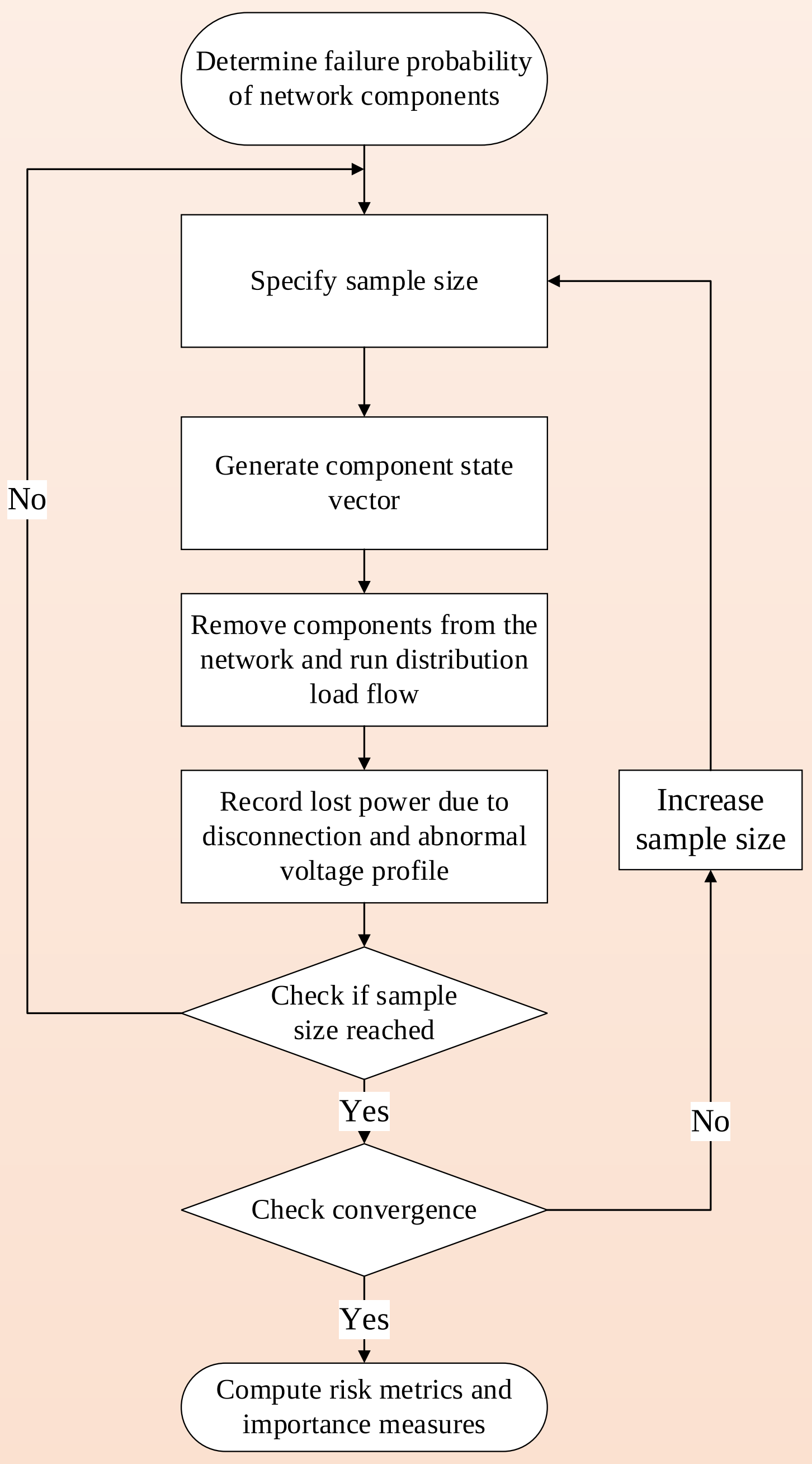
$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(k)} = \begin{bmatrix} \frac{\partial P}{\partial \delta}\Big|_{\delta^k} & \frac{\partial P}{\partial |V|}\Big|_{|V|^k} \\ \frac{\partial Q}{\partial \delta}\Big|_{\delta^k} & \frac{\partial Q}{\partial |V|}\Big|_{|V|^k} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix}^{(k)}$$

$$\begin{bmatrix} I_1^{1\times 1} \\ I_2^{(n-1)\times 1} \end{bmatrix} = \begin{bmatrix} Y_{11}^{1\times 1} & Y_{12}^{1\times (n-1)} \\ Y_{21}^{(n-1)\times 1} & Y_{22}^{(n-1)\times (n-1)} \end{bmatrix} \begin{bmatrix} V_1^{1\times 1} \\ V_2^{(n-1)\times 1} \end{bmatrix}$$

- Initialization: iteration count $= 1$, $V_i^{(1)} = 1\, p.u.$, form $\boldsymbol{Y}_{22}$, specify swing bus voltage V_s
- Step 1: Compute injected current for each load bus $I_i^{(k)} = -(\frac{P_i + jQ_i}{V_i^{(k)}})^*$
- Step 2: Compute voltage deviations due to loads $\boldsymbol{I}^{(k)} = \boldsymbol{Y}_{22}\Delta\boldsymbol{V}^{(k)}$
- Step 3: Update voltage $\boldsymbol{V}^{(k)} = \Delta\boldsymbol{V}^{(k)} + \boldsymbol{V}_s$
- Step 4: Check if the voltage meets convergence criteria. Otherwise increase k by 1 and go to Step 1

Simulation

- The substation component states are represented by a random binary vector where each entry is a Bernoulli random variable taking values of either 0 or 1 with a certain probability that is determined by the fragility function and ground motion intensity that each component is subjected to.
- The failure probability of substation outgoing feeders are determined by those of the substation components and their dependencies
- After the status of outgoing feeders are determined, distribution load flow is performed with active substation feeders and network buses.
- Loss of load can be attributed to loss of connection or abnormal voltage profiles.
- Monte-Carlo simulation (MCS) is used to obtain the probability distribution of the unserved demand, from which risk metrics are computed.


Determine failure probability of network components

Specify sample size

Generate component state vector

Remove components from the network and run distribution load flow

Record lost power due to disconnection and abnormal voltage profile

Check if sample size reached

Check convergence

Compute risk metrics and importance measures

Increase sample size

No

Yes

No

Yes

Figure 3 CIGRE medium voltage distribution test system

Results

Performance of single/double bus bar substation configuration with meshed/radial network structures are compared in terms of

- Probability distribution of load not served
- Expected load not served
- Risk achievement worth and risk reduction worth

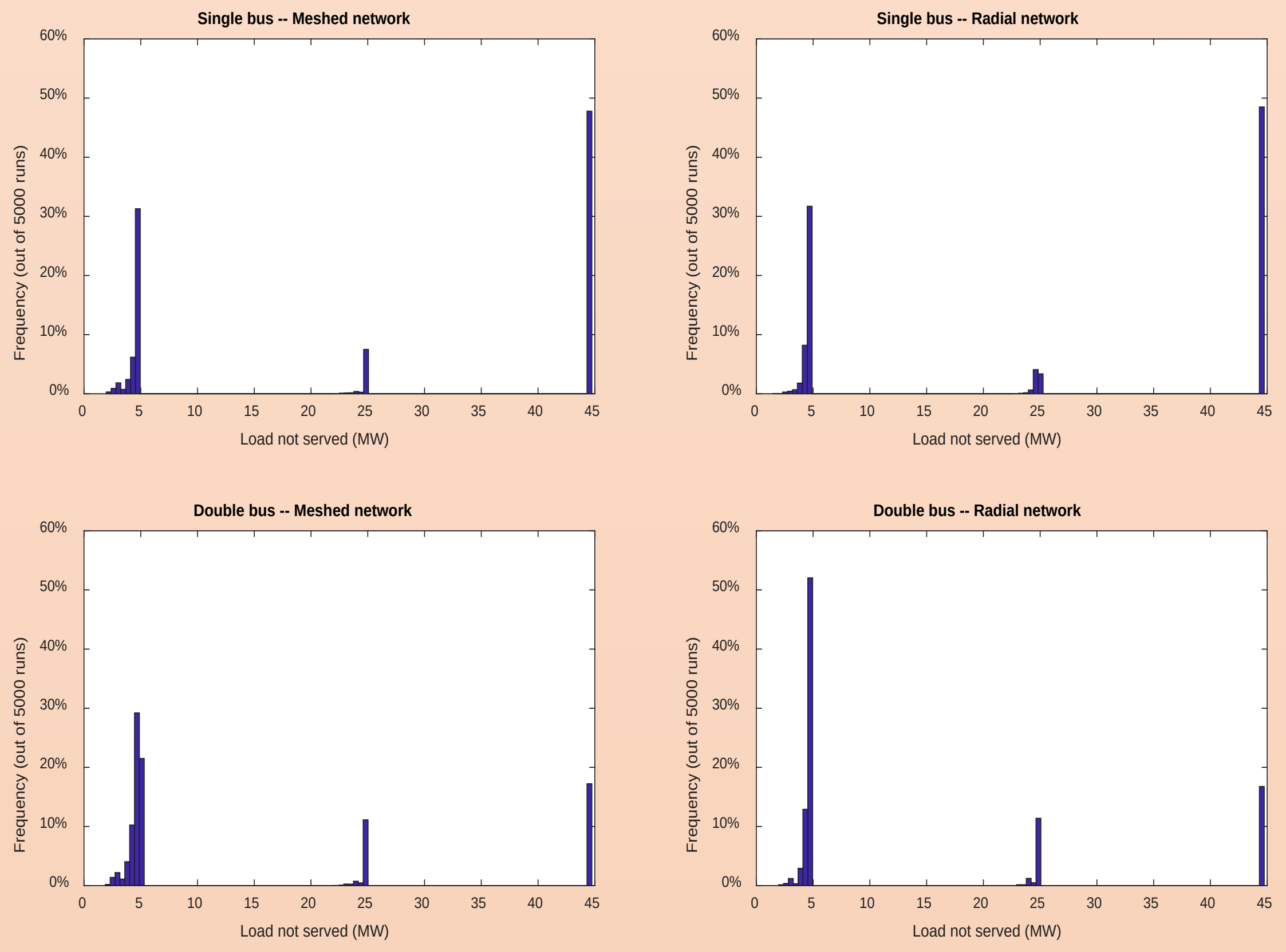


Figure 4 Histogram of unserved load for different combinations of single/double bus substation layouts and radial/meshed network topologies.

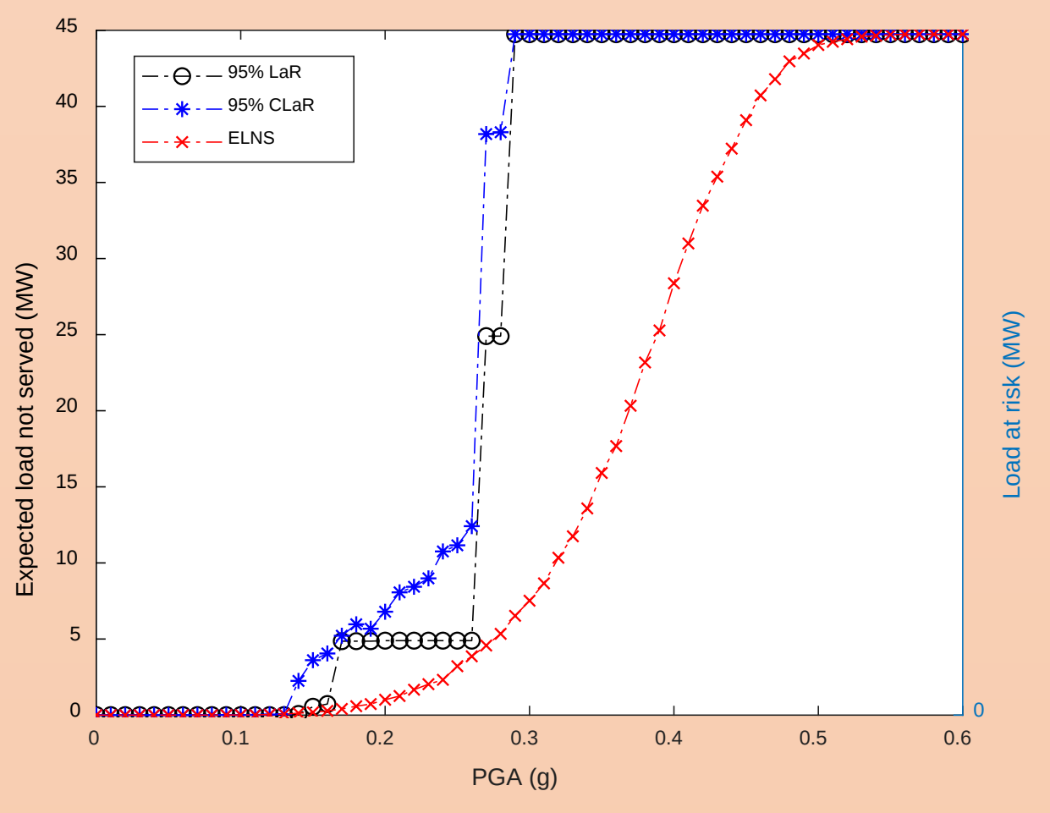


Figure 5 Risk metrics as a function of PGA

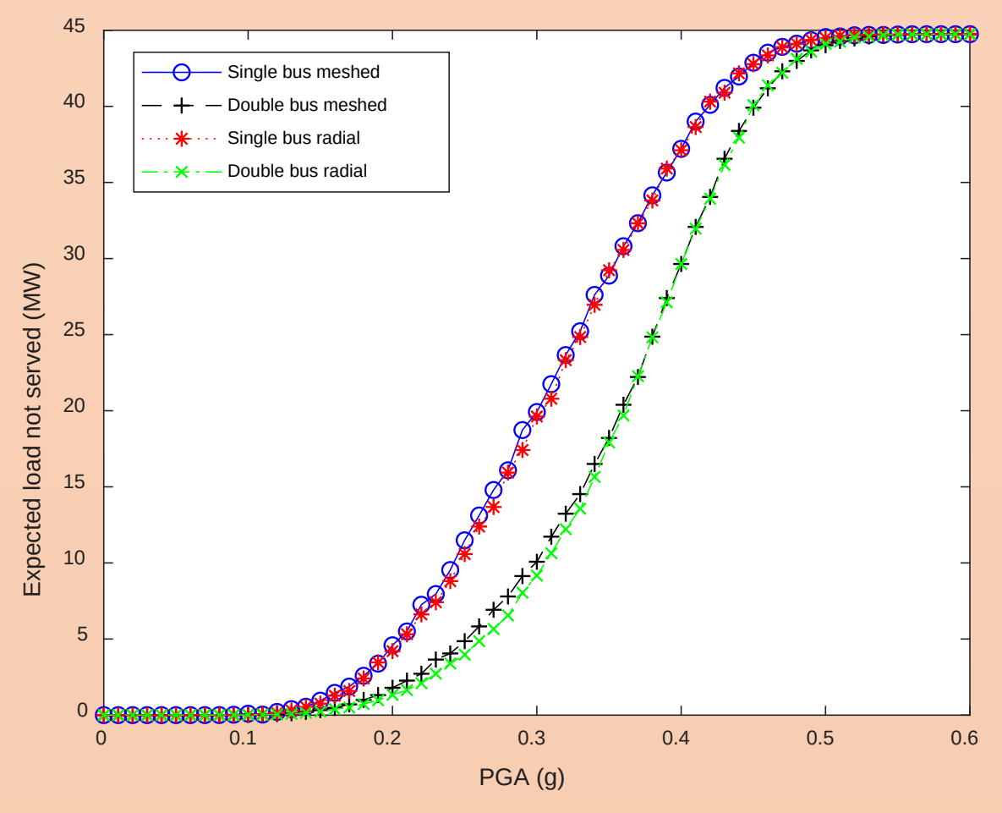


Figure 6 Expected load not served as a function of PGA for combinations of single/double bus substation configurations and radial/meshed network topologies.

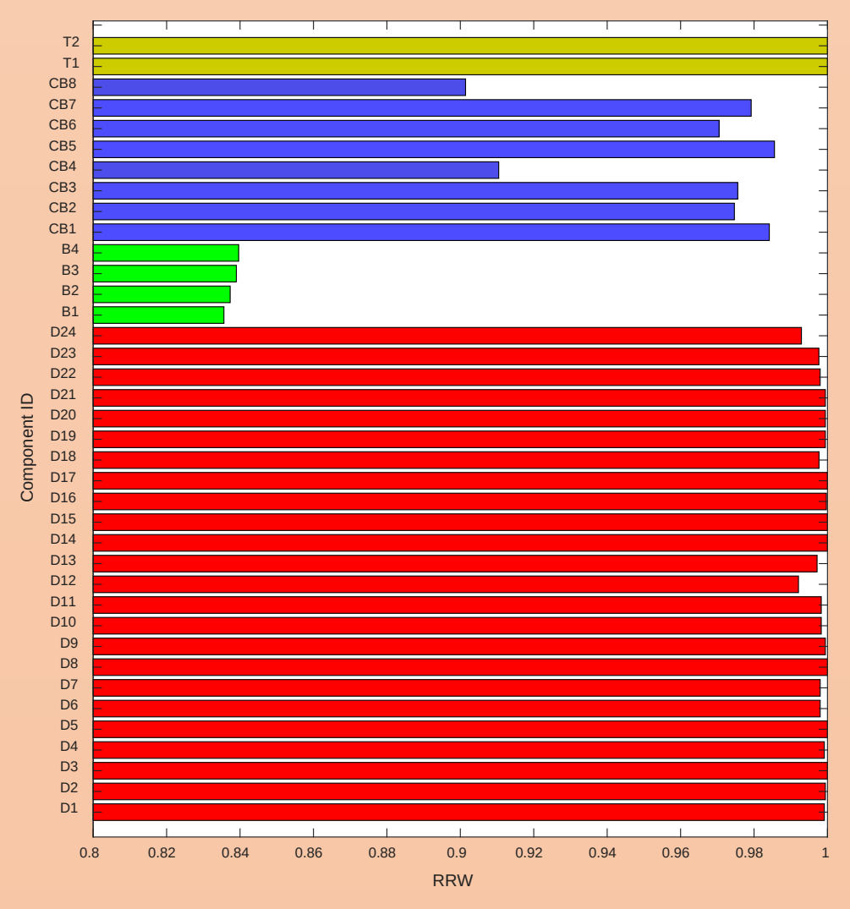


Figure 7 RRW of substation components in terms of ELNS

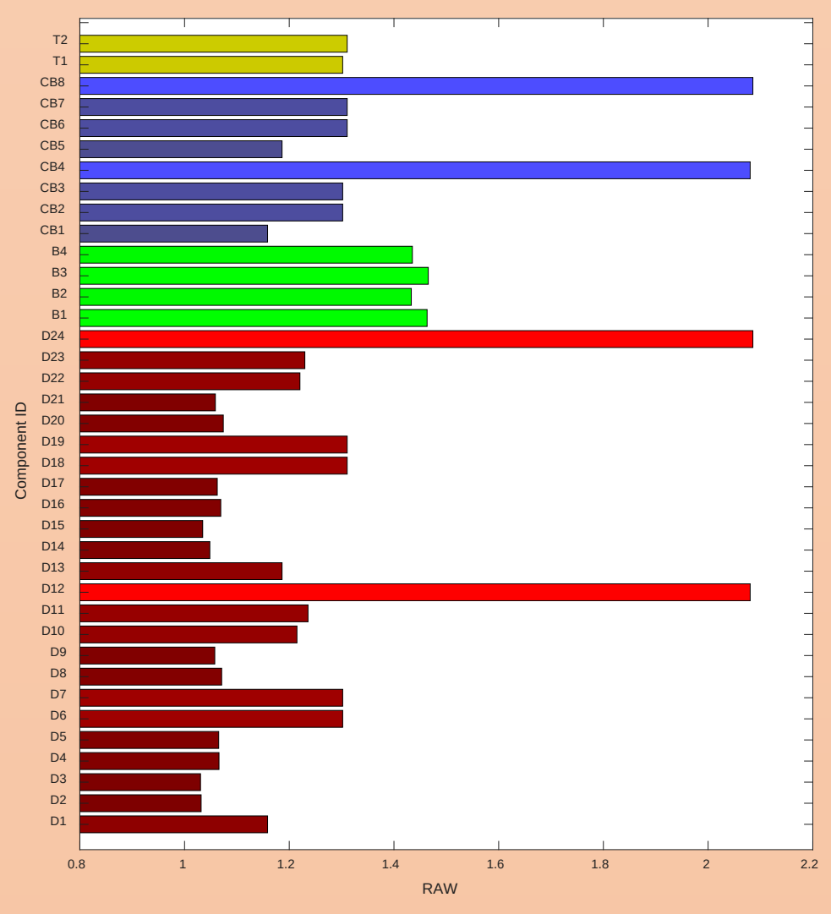


Figure 8 RAW of substation components in terms of ELNS