A Novel Formulation of LV Distribution Network Equivalents for Reliability Analysis

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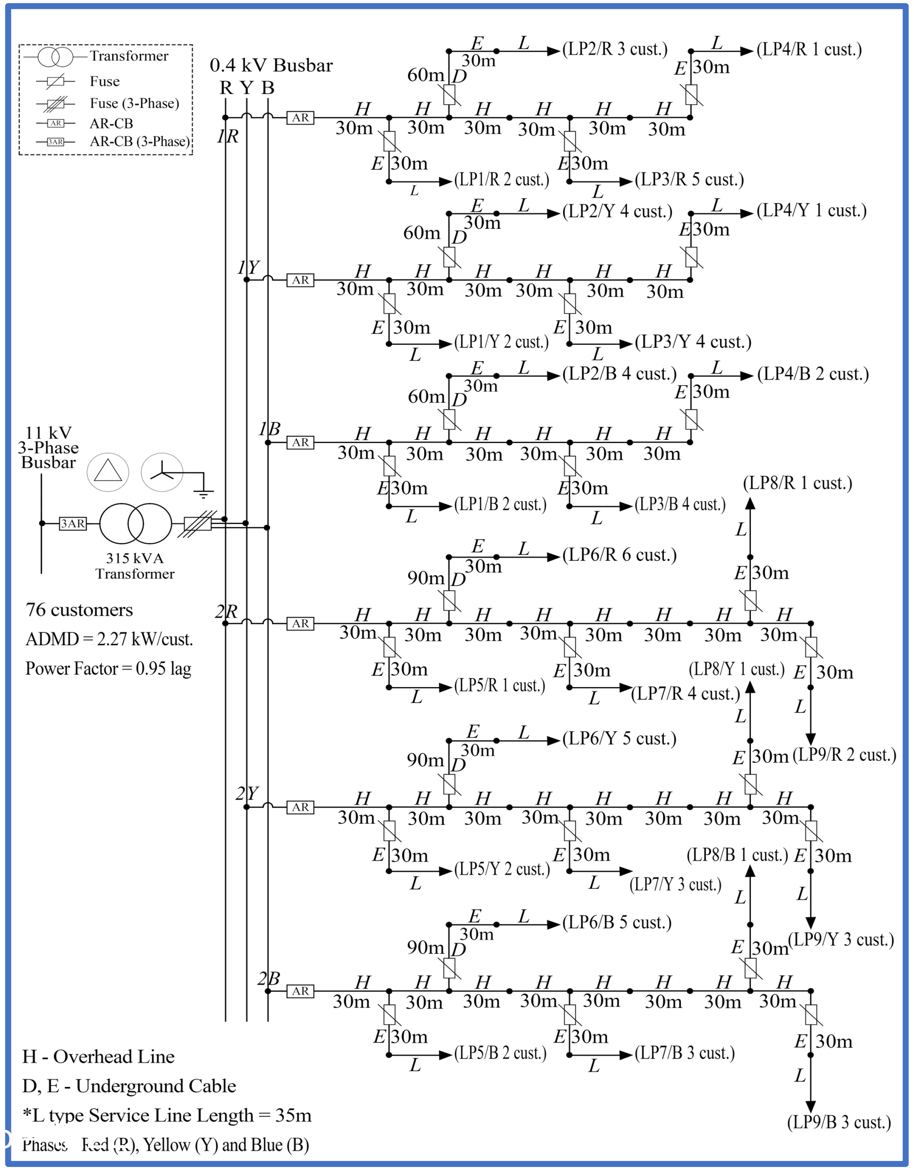
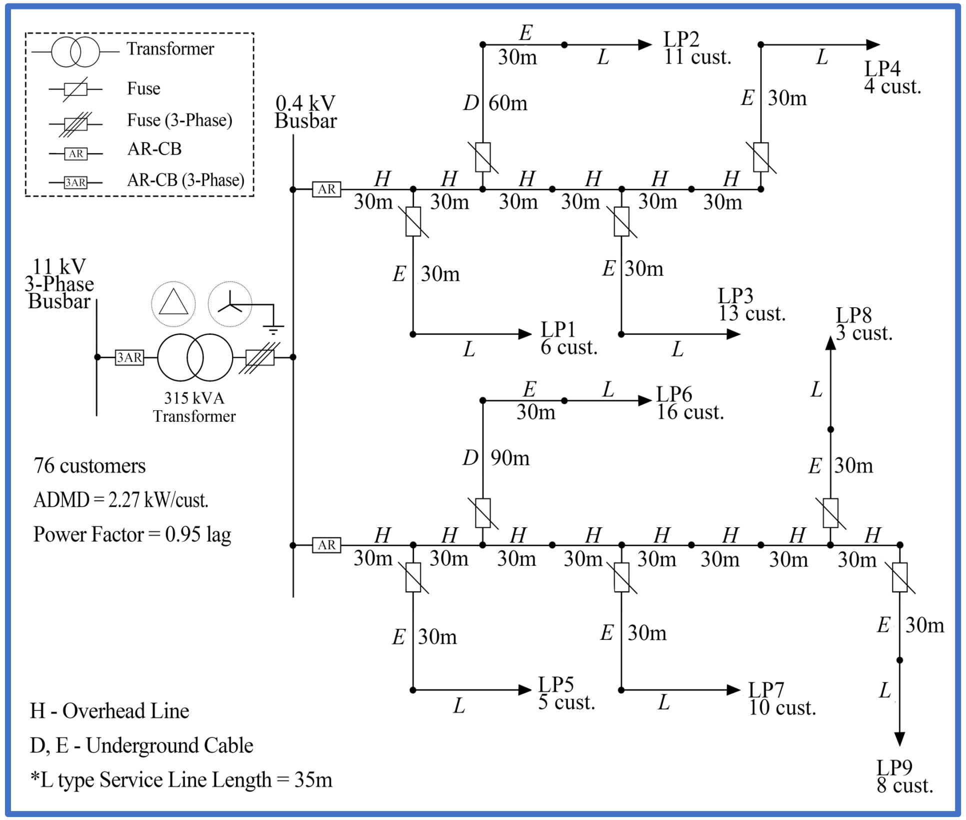
Single-Line (1-ph) *vs* Three-Phase (3-ph) Models

Three-phase model of an ‘unbalanced’ (& realistic) generic suburban LV network

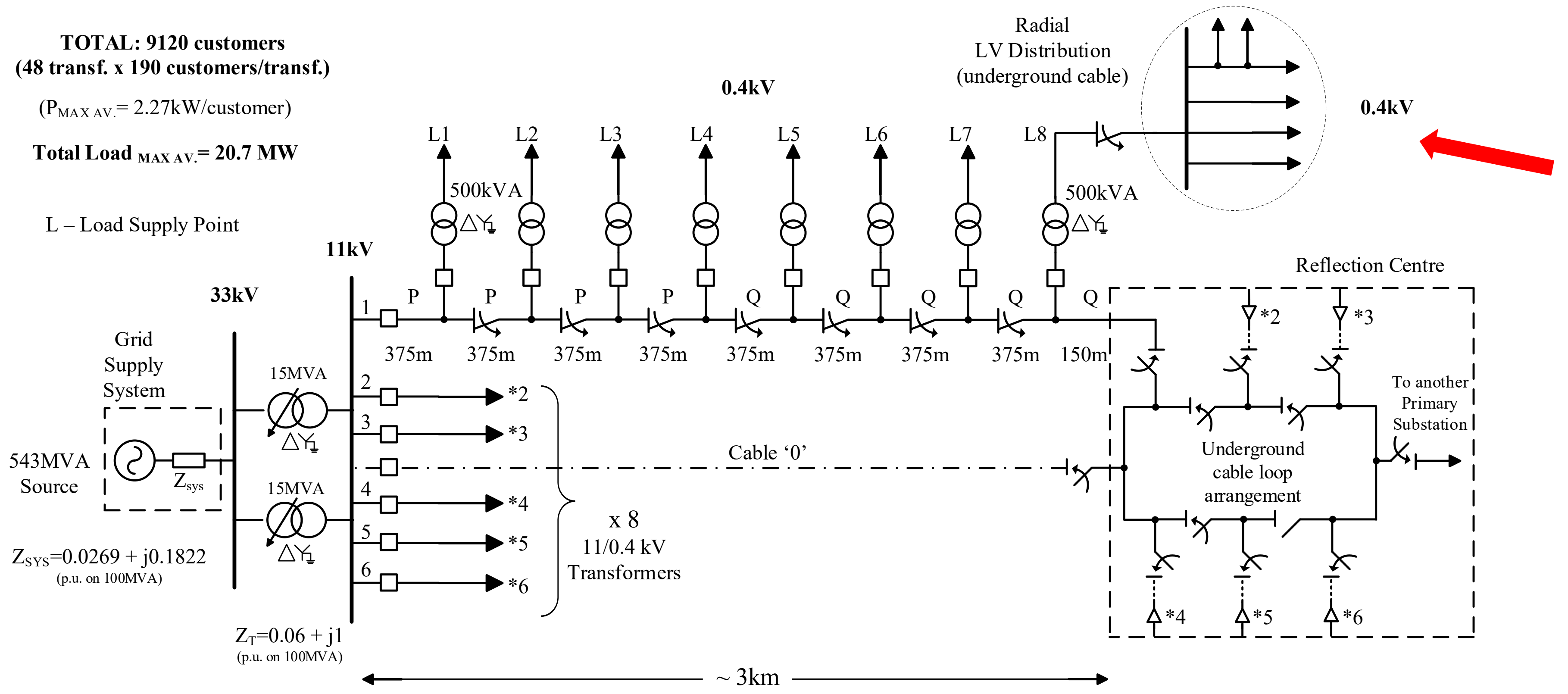




Single-line model of a ‘balanced’ generic suburban LV network

Ignores phase-connection of customers, and protection system components (single-pole vs three-pole)

Reliability Performance of MV networks



Volume and complexity!

Use lumped aggregate model for each LV network with total load & number of customers

Reduce computation times for reliability assessment

Inaccurate representations

- Neglect the highly dispersed loads and
- different component types

- Large cumulative errors
- Incorrect characterisation of the quality of supply for different customers
- Affects network planning and operation

State Enumeration

- **State Enumeration (SE)** is used to perform reliability analyses of large networks.
- Usually, for a system of m **repairable** components, there are 2^m system states.
- Each state is a combination of the status of different components (UP/DOWN).
- It is **not computationally feasible** to enumerate all system states for large systems.
- Usually, the **analysis stops** at a given enumeration depth (ED), which corresponds to a failure level.

$ED_k = C_0^m + C_1^m + \cdots + C_k^m$	For a system of *k* = 97 components:	System states with:
$ED_1 = C_0^m + C_1^m$	ED1 = $C_0^{97} + C_1^{97} = 98\ states$	Only 1 component failure
$ED_2 = C_0^m + C_1^m + C_2^m$	ED2 = $C_0^{97} + C_1^{97} + C_2^{97} = 4754\ states$	Only 2 component failures

State Enumeration cont'd

- The **frequency of occurrence** of each system state and the **mean duration** of residing in each state is based on the **failure and repair rates of components**.
- The impact of each selected state must be identified in terms of the interrupted loads/customers.
- Sequential **Monte Carlo Simulation (MCS)** can then be used to calculate reliability indices based on an artificial cycle of system operating and failure states.

Considering only low-order contingencies

- Reduced computational efforts without significantly impacting accuracy
- Successive transitions between two system failure states are very rare.

Considering only high-order contingencies

- System resilience
- Protection design & control

Sequential Monte Carlo Simulation

- Sequential MCSs are usually performed using state duration sampling (SDS)
- Each component is assigned a mean failure rate and mean repair time
- Creating a state transition process of the up and down cycles of all system components.

BUT

- The SE-reduced number of states (r) **do not distinctly equate to an equivalent number of components**.
- For example, $r = C_0^{97} + C_1^{97} = 98$ states for ED_1 of the Single line model.
- This corresponds to a fictitious number of components between 6 ($2^6 = 64$) and 7 ($2^7 = 128$).

- **SO**, we use sequential MCS based on **state transition sampling (STS)**
- STS focuses on **state transitions** of the entire system, rather than on the individual component states
- The system will transit from one system state S_k into the next state S_{k+1} depending on the random state duration of the component that first departs from its present state (up or down) in system state S_k

Sequential MCS cont'd

The probability of the j^{th} component departing from present state at time t_0 is:

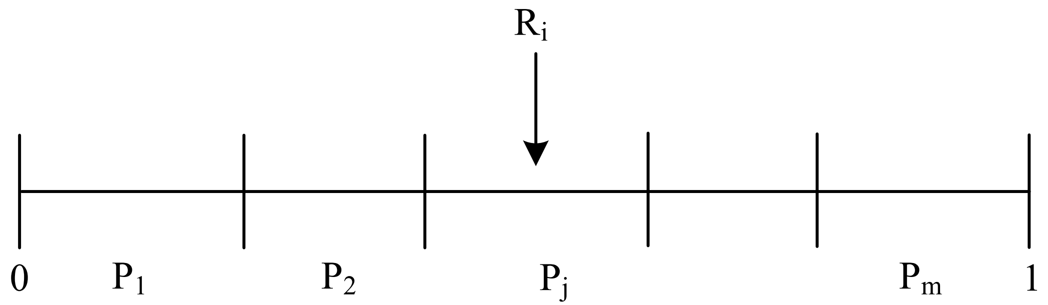
$$P_j = \frac{\lambda_j}{\sum_{i=1}^{m} \lambda_i}$$

$i = 1, 2, \ldots, m$, where m is the number of components

- The state transition of any component leads to a state transition.

  For m components, there can be m possible reached states.

- The probability of the m states that could be reached can then be successively placed in the interval [0,1] (because $\sum_j^m P_j = 1$)



Generate a uniformly distributed random number R_i between 0 and 1.

- Assess the consequences of each system state, i.e., the impact on frequency and duration of customer interruptions.

- Simulation is repeated until the required accuracy ε

$$\varepsilon = \sqrt{var(x)}/(\bar{x} \cdot \sqrt{N})$$

Formulation of Reliability Equivalents of LV Networks

SE-reduced network (with ED_1 or ED_2 states) ⟷ Same Unavailability ⟷ An equivalent single-component reliability model, with equivalent failure (λ) and repair rate (μ)

- Formulate **Unavailability (*U*)**, using **Energy Not Supplied (ENS)**.
- ENS combines both frequency- and duration-based indices.
- It is a **composite reliability performance indicator** that quantifies the combined effects of the numbers and durations of supply interruptions with the amount of interrupted demand.

$$\lambda_{eqv} = SAIFI \times LPs$$

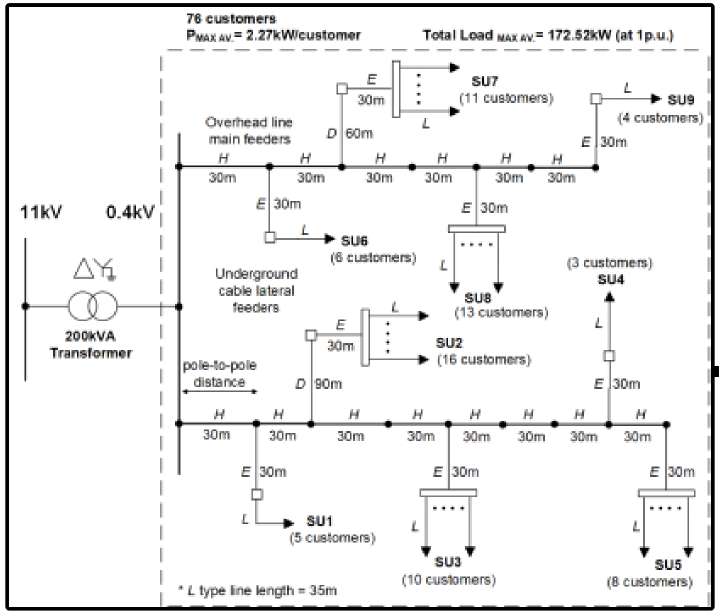
$$U = \frac{Annual\ ENS}{Connected\ demand \times hours\ in\ a\ year}$$

$$U = \frac{\lambda_{eqv}}{\lambda_{eqv} + \mu_{eqv}}$$

$$\mu_{eqv} = \frac{(1-U)\cdot\lambda_{eqv}}{U}$$

$$MTTR_{eqv} = \frac{1}{\mu_{eqv}}$$

State Enumeration and Monte Carlo Simulation Techniques



- Detailed LV model
- Time-consuming MCS

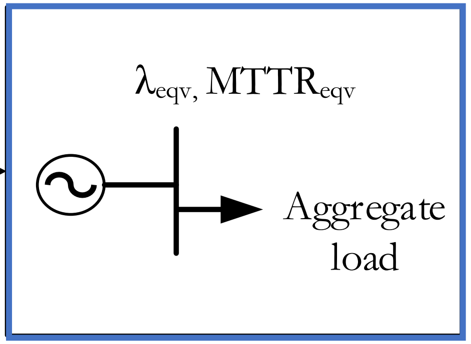
SE+MCS →

ED System States

Reduced number of states and accurate reliability indices

- Minimum error
- Faster MCS

Equivalenting →

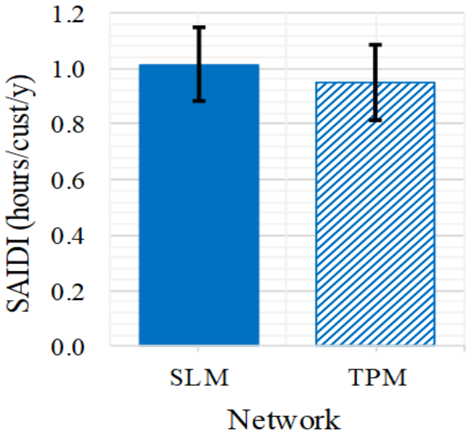


- Equivalent PC
- Same unavailability

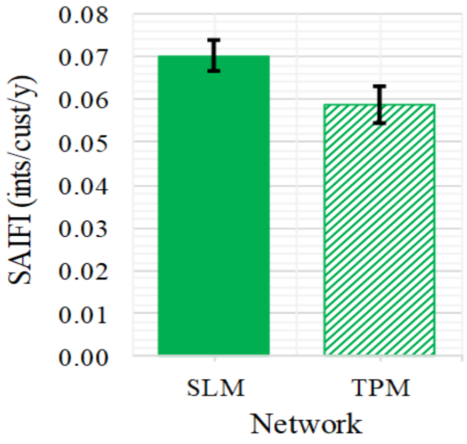
TPM Single Equivalent Component Parameters

Eqv-PC	λ_{eqv} (failures/year)	$MTTR_{eqv}$ (hours)	Computational Time Saving (%)
TPM	1.555	0.588	99.98%

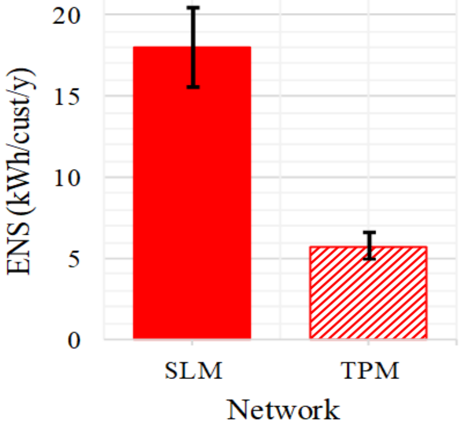
Single-Line (1-ph) *vs* Three-Phase (3-ph) Models



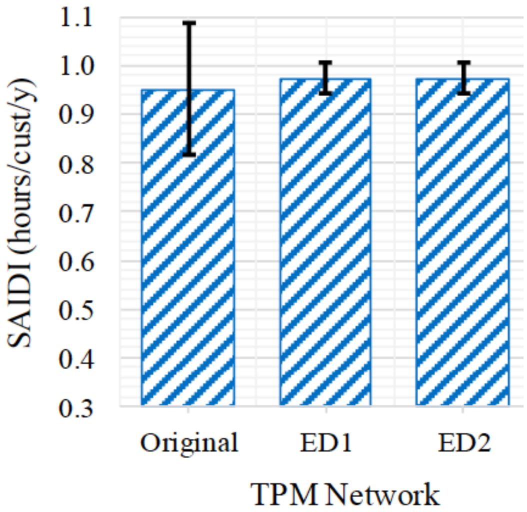
(a) SAIDI



(b) SAIFI



(c) ENS



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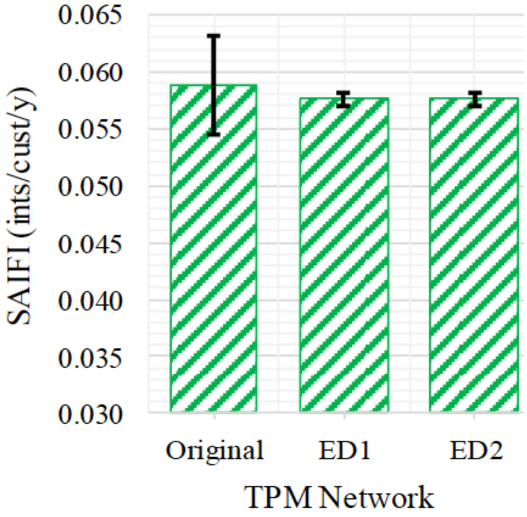
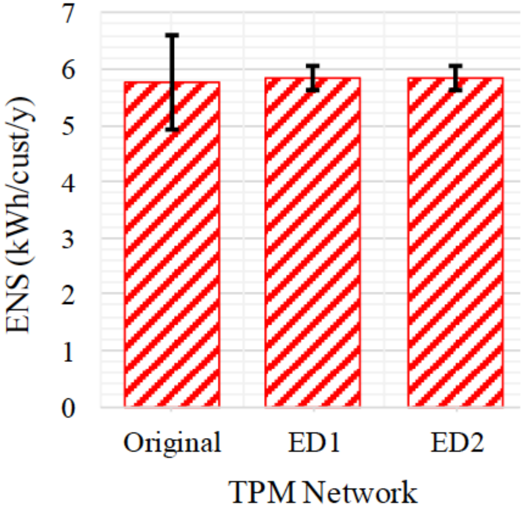


(b) SAIFI



(c) ENS

- TPM is **more accurate**;
- Detailed representation of the actual network;
- SLM **underestimates** reliability performance, mainly for ENS;
- TPM differentiates different fault types.

- Low-order EDs are **sufficient** to assess reliability performance with **high accuracy**, while requiring significantly **shorter computational times**.

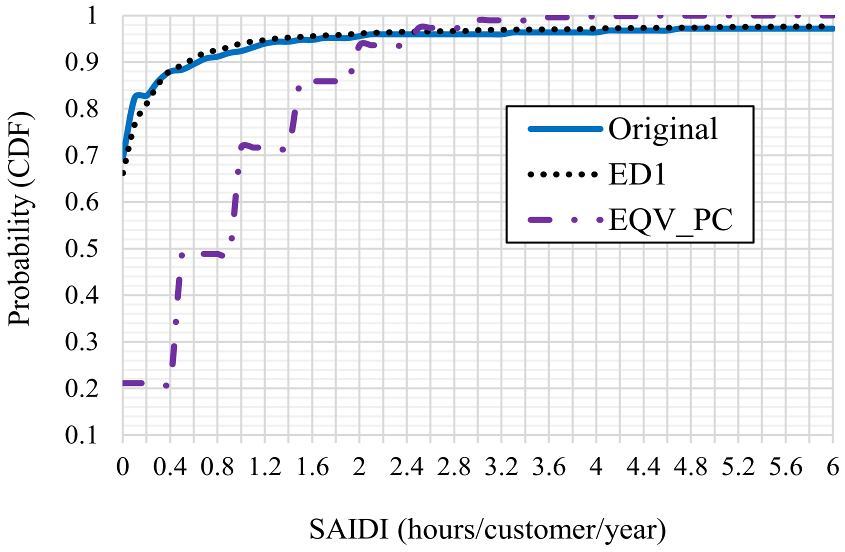
Combining SE and SMCS for LV Reliability Equivalents

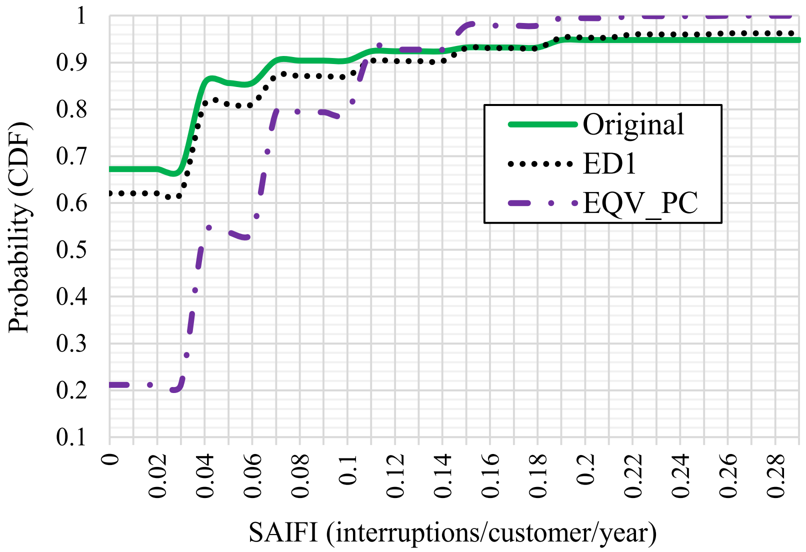
- ED_1 and ED_2 produce **nearly identical** results - due to the low probability of double faults.
- ED_2 results in much longer simulation times than for ED_1
- Computational time is reduced by **99.9% for ED_1** and by **91.1% for ED_2** models compared to original network.
- The time required to perform **equivalenting** is also higher in ED_2 (33.8 hours) than ED_1 (2.5 hours)
- ED_1 is **sufficiently representative** of the original network.

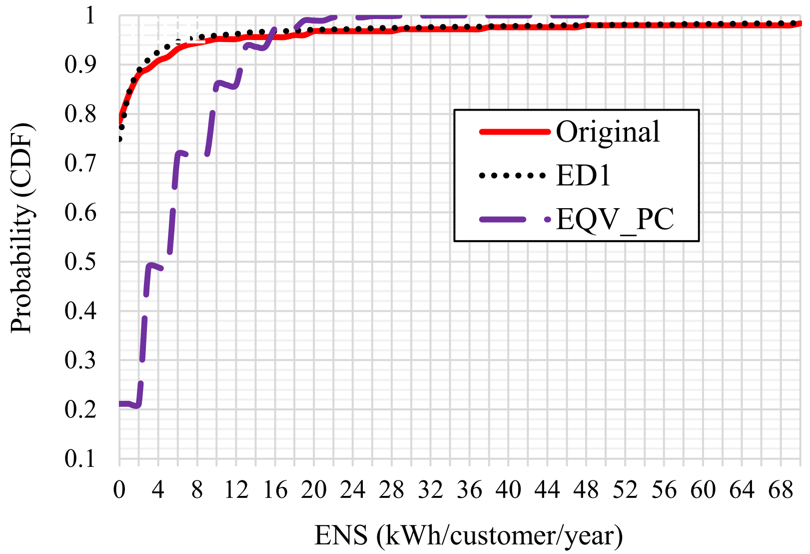
Reliability Indices for the TPM Equivalent Component.

Network	**SAIDI**		**SAIFI**		**ENS**	
	hrs/c/y	**Error**	**ints/c/y**	**Error**	**kWh/c/y**	**Error**
Orig.	0.9508	-	0.0588	-	5.7648	-
ED_1	0.9739	2.4%	0.0576	2.0%	5.8437	1.4%
Eqv-PC	0.9154	3.7%	0.0577	1.9%	5.8485	1.5%

Combining SE and SMCS for LV Reliability Equivalents



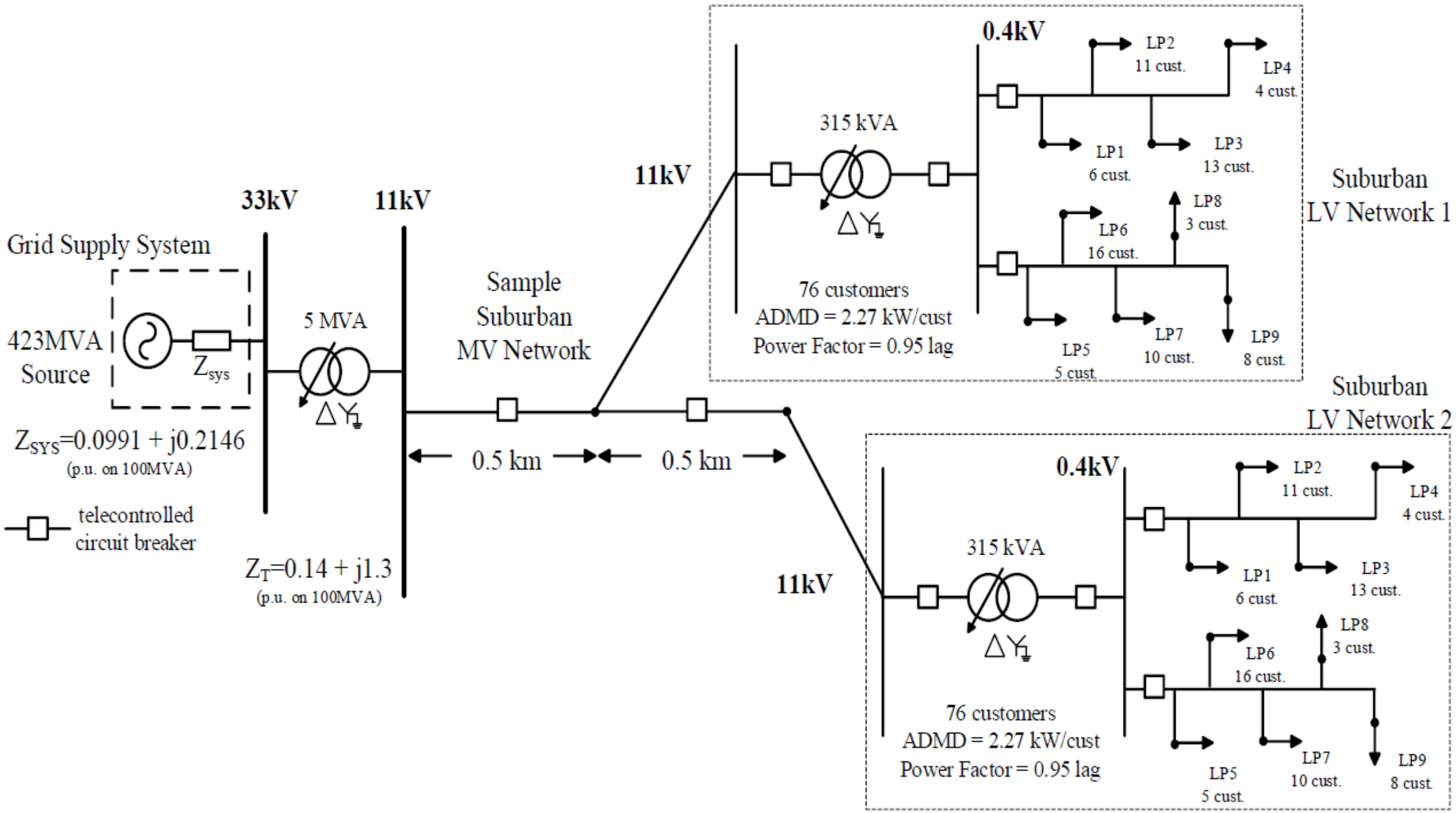




- Combined SE−SMCS (ED_1) $\equiv$ *Original network*
- Eqv-PC aggregates composite reliability information
- Still adequately approximates the CDFs of the detailed original network with a higher number of components.
- Quantifying the risk of longer interruption times, frequency and ENS.

Analysis at MV Level with LV Network Equivalents

“Plug and Play” functionality



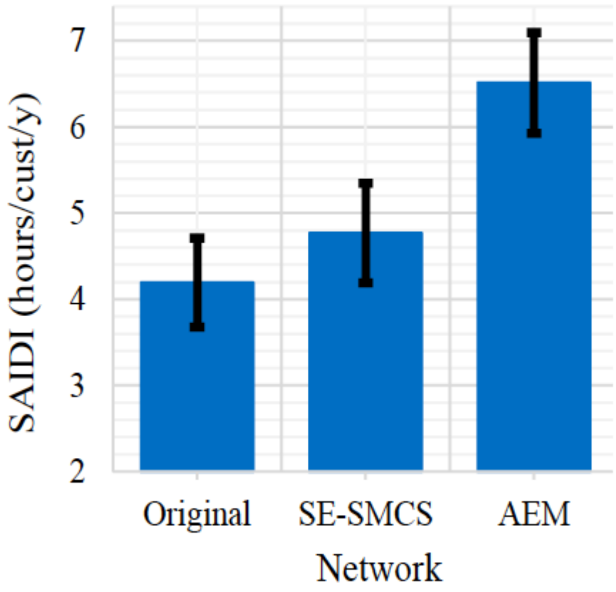
Original (SLM) suburban MV network model with 213 components

Comparison of Results (at MV) of Two Single-Component (LV) Models

Eqv-PC	λ_{eqv} (failures/year)	$MTTR_{eqv}$ (hours)
SE-SMCS	1.052	1.217
AEM	0.472	6.235

SE-SMCS approach:

- Location of components;
- Impact of failures;
- Does not increase complexity;
- Reliability dependency between MV and LV networks.



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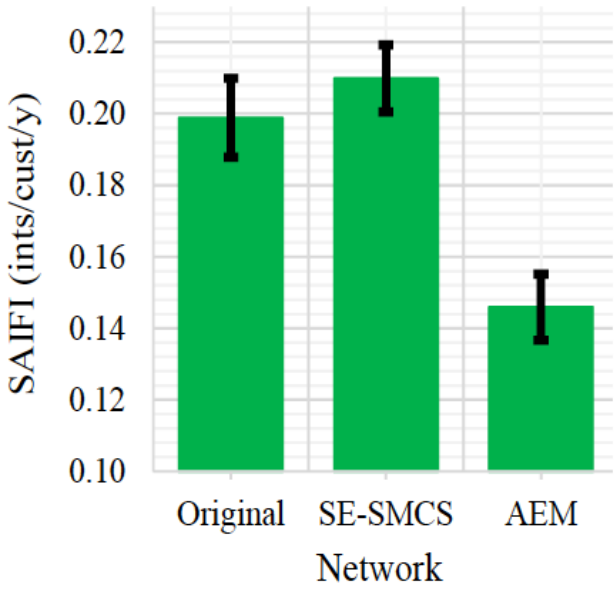
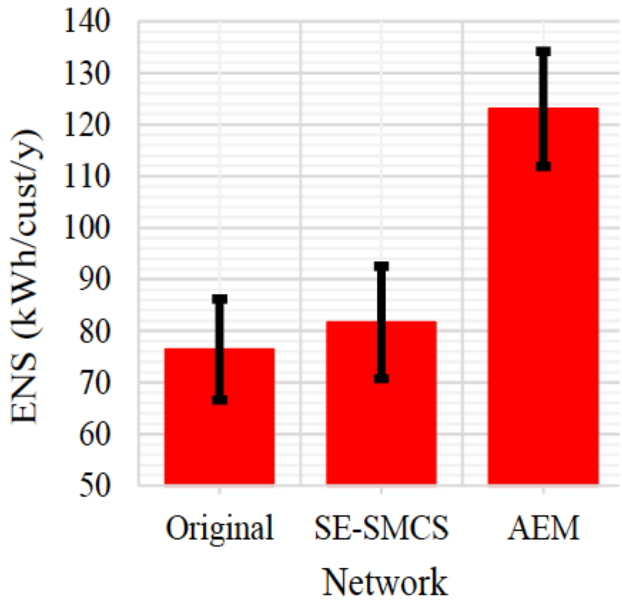


(b) SAIFI



(c) ENS

Conclusions

- A novel comparison of the (typically used) simplified SLMs of LV networks, in contrast with fully detailed TPMs, which **avoids systems' performance overestimation**.

- Development of a novel LV/MV network reliability assessment methodology that **combines SE and SMCS** to significantly reduce computational complexity while preserving accuracy.

- Development of a novel and simple **single-component network equivalent**, which offers the same **unavailability** (and therefore reliability performance) as the original LV/MV network.

- Accuracy, computational efficiency and scalability of the proposed LV equivalents is tested and validated in more complex and larger MV networks, for **replicability** of the proposed methodology.

Thanks for listening.
Any Questions?

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