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**ON THE OPTIMAL PLACEMENT OF POWER DISTRIBUTION  
NETWORK LINES**

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**Introduction.** Reliability is primarily related to component failures, end-user interruptions, and repair times. These depend on the system’s response and component failures to predict the reliability of the electrical system. To achieve this, reliability indices are utilized to help us respond optimally in the shortest possible time when restoring the power supply. MTBF quantifies the reliability of repairable equipment by dividing the total operating hours by the number of failures. This metric is used in this analysis because components are restored after each failure. Decreasing MTBF reduces the frequency of interruptions and improves the overall reliability of the system [1]. The mean time to

repair is the time it takes to repair a system. In power systems, the network must be both reliable and efficient. To operate a network effectively, it is essential to manage it in a centralized manner to achieve optimal power flow [2]. A very high-speed communication infrastructure is required to make this type of optimization converge to the solution with fewer interactions [3]. This research will utilize the TLBO (Teaching-Learning-Based Optimization) algorithm, which is employed to solve optimization problems. This algorithm can find the optimal point and is ideal for solving problems with a large and complicated computational load, as well as reduced reaction times [4].

The TLBO algorithm employs a mathematical model for teaching and learning, but it does not account for the system's reliability, as it requires a power supply to function. When a failure occurs, the redundant system replaces the non-operating or faulty component. With this redundancy system, power supply interruptions can be avoided. The repair of a defective component is subject to certain restrictions associated with failures, which reveal variables such as the mean time to repair (MTTR). If the element does not meet the MTTR threshold, it is taken out of operation. In parallel redundancy, all components operate simultaneously. This is implemented when the system needs to remain functional without interruption.

**Purpose and objectives.** The predictive reliability study is based on the failure rate cycle, represented by a bathtub curve. It utilizes the standard Weibull distribution to determine the slope of the failure rate in each period, employing median range regression for parameter estimation. The bathtub curve leads to the insertion of parameters, such as the total factor deterioration index (TFDI), through linear trend regression of the parameters on a logarithmic scale of their useful life. One of the strategies to improve reliability is to install reclosers in an optimal manner, which isolate faults in a few seconds and thus mitigate interruptions to the end user. The aim is to study the effect on SAIFI and SAIDI reliability indices in the ETAP software.

The implementation of smart grids guarantees continuous power while maintaining system reliability. The Monte Carlo method is applied in a stochastic study, which involves a sequential time system that identifies events in temporal order, generating a sequence of repair cycles that focus on both repair time and failure time. In any electrical

or electronic system, system continuity must be ensured, and the extension of the redundant system would reduce failure and repair times. In the event of a failure, the  $N+1$  redundant system will replace the failing hot component, thus avoiding process interruptions [5].

The repair of a defective component is subject to certain restrictions associated with failures, which reveal variables such as the mean time to repair (MTTR). Still, in practice, most systems are connected in parallel with another element. In parallel redundancy, all components operate simultaneously. This is implemented when the system needs to remain functional without interruption. Redundancy leads us stochastically to consider some random variables, such as the useful life of the components in a redundant parallel system, resulting in a marginal exponential distribution. Then,  $T_{max}(X, Y)$  has the following reliability function:

$$R(t) = P(\min(X, Y) > t) = F_{X,Y}(t, t) = e^{-2\lambda t} (1 + \alpha - 2\alpha e^{-\lambda t} + \alpha e^{-2\lambda t}).$$

Redundant components that are on standby function when the system has a failure. This method is used when component replacement does not require a lengthy process and does not cause further system failure. The convolution of the variables is estimated stochastically, giving us  $T=X+Y$ .

**Research material and results.** The proposed methodology is validated using the “MV Distribution Network – Base Model” integrated into the DigSilernt PowerFactory. This test system represents a medium-voltage distribution network with realistic characteristics, commonly used in reliability studies, load flow analysis, and contingency assessment in electrical systems. The model structure comprises four primary substations, designated as SUB\_01 to SUB\_04, which cover over 270 connection nodes and approximately 300 distribution lines. Fig. 1 shows the single-line diagram of the test system in question. The evaluation continues with an analysis of the effects that these selected locations have on the system’s reliability indicators, fundamental parameters that characterize the operational performance of the distribution network. Subsequently, the changes in the electrical behavior of the system are evaluated, considering critical

operational variables such as voltage profiles at different nodes, power flows through transmission lines, and total energy losses in the system. The implementation of the valid solution with three redundant lines resulted in quantifiable improvements in reliability indicators, as evidenced by an increase in the average MTBF from 403.64 hours to 409.42 hours and a reduction in MTTR from 2.351 hours to 2.306 hours, as shown in Fig. 2. These variations reflect a lower frequency of component failures and faster recovery after each event, confirming that the optimized location of redundant lines using the TLBO algorithm has a positive influence on the reliable performance of the electrical distribution system under analysis.

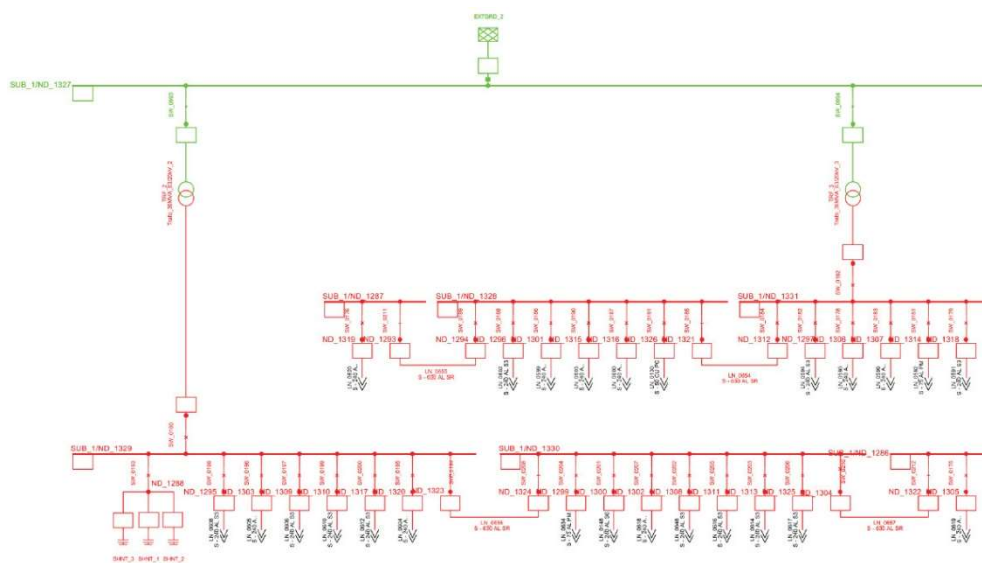


Figure 1. Single-line diagram of the “MV Distribution Network – Base Model” test system

Analysis of the voltage profile (Fig. 3) reveals that, without redundant lines (red line), the most significant drops are concentrated near nodes 1500 and 2000, with minimum values of approximately 0.94 p.u. In contrast, with redundant lines (blue line), the minimum values are located around node 2000, remaining around 0.95 p.u. and with less dispersion. However, the rest of the nodes maintain a magnitude of around 0.98 p.u. These results show that the inclusion of redundant lines substantially improves the voltage profile. These results indicate that redundant lines reduce angular dispersion, moderately improving synchronization between nodes.

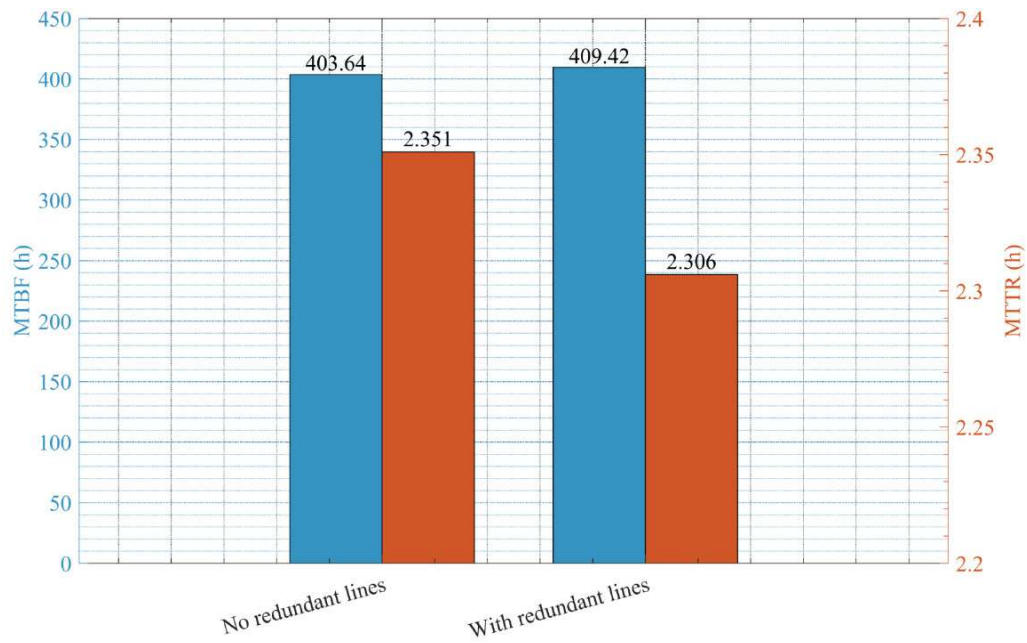


Figure 2. Comparison of MTBF and MTTR reliability indicators

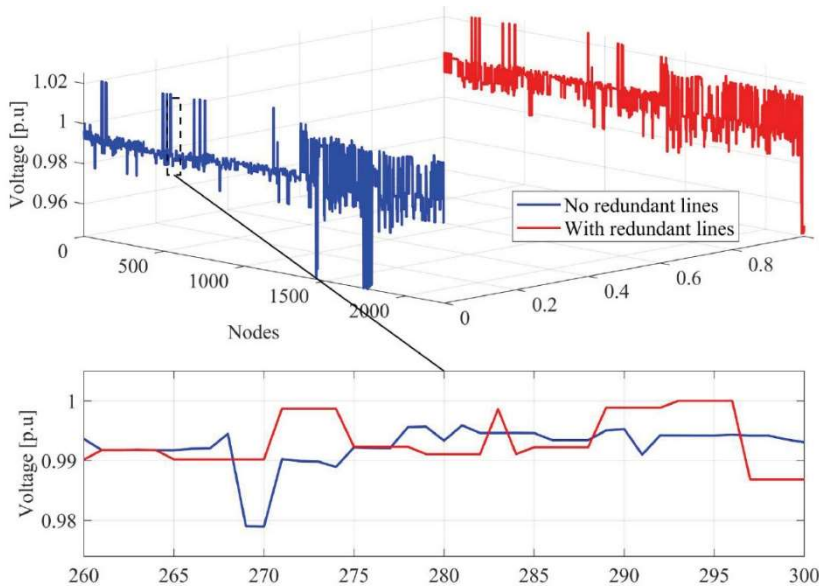


Figure 3. Comparative analysis of voltage profiles with and without redundant lines

The distribution of active power per line, as shown in Fig. 4, undergoes significant changes after the implementation of redundant lines. This transformation converts a

system that initially exhibits high variability, with flows exceeding  $\pm 5000$  MW in several sections of the network, into a configuration where values are concentrated in a more contained range with less overall dispersion. In detail, although some points experience a reduction in power magnitude, a more uniform distribution between lines is achieved, reducing local overloads by providing alternative routes for energy flow. This allows power to be distributed across multiple paths rather than concentrated on a few specific lines, favoring a more balanced operation of the distribution system.

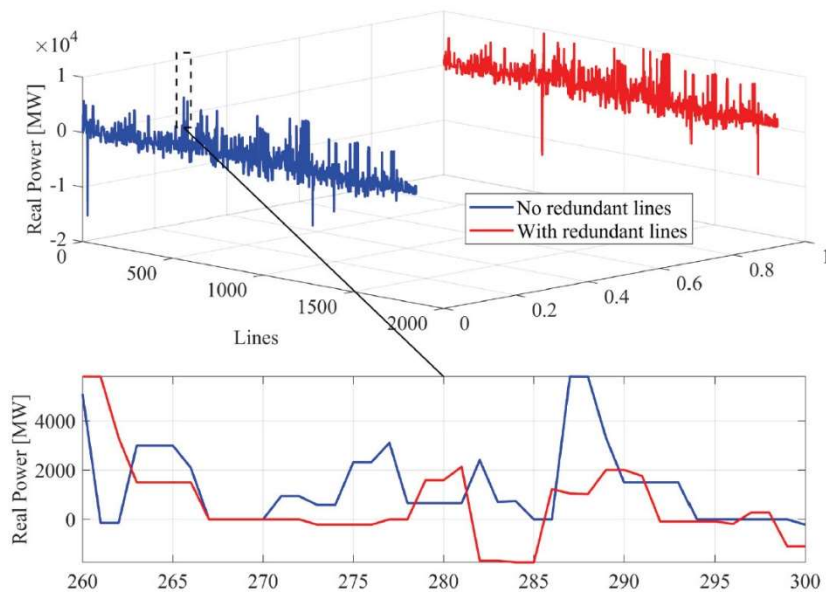


Figure 4. Comparative analysis of real power with and without redundant lines

The application of the TLBO algorithm successfully achieved the specific objectives set out in the research. The challenges related to reliability and downtime were clearly identified, highlighting the need for redundant lines to improve the operational performance of the system. Through the analysis and evaluation of mean time between failures (MTBF) and mean time to repair (MTTR), it was determined that the best solution obtained corresponds to the incorporation of three redundant lines (LN-1011, LN-1058, and LN-0871), due to their greater statistical stability and lower variability in results. Simulation of the distribution system under defined scenarios quantitatively confirmed the improvement in reliability, increasing the MTBF from 403.64 h to 409.42 h and

reducing the MTTR from 2.351 h to 2.306 h. The average load capacity of the lines increased, confirming a more efficient use of the existing electrical infrastructure.

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