RESEARCH ARTICLE

Economic Effects of Measures for Reducing Losses in Electrical Distribution Network within the Transition to a Sustainable Active Distribution System

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Abstract

This paper provides a comprehensive analysis of the economic implications of implementing advanced loss-reduction measures in electrical distribution networks, as observed across developed economies. The study evaluates a set of technical and infrastructural interventions that have demonstrated significant potential in enhancing network efficiency and reducing operational losses. These measures encompass the large-scale deployment of smart electricity meters, the replacement of conventional distribution transformers with units employing amorphous metal cores, and the mitigation of transformer overloading through the installation of higher-rated capacity units. Additional strategies include increasing the cross-sectional area of distribution conductors, optimizing feeder configurations by extending medium-voltage lines, shortening low-voltage feeders, and relocating substations closer to feeder midpoints. Moreover, the paper examines the transition from the conventional "one substation–multiple feeders" configuration toward a more efficient "one substation–one feeder" supply concept. The results of the analysis confirm that the implementation of these measures is both technically and economically justified, yielding substantial improvements in network performance, energy efficiency, and long-term operational sustainability.

Keywords: electrical distribution network, losses, profitability, reconfiguration.

1 Introduction

Before the intensified use of distributed sources, the electrical distribution network was treated as a passive part of the rest of the power system, and therefore was not a subject of interest regarding preventive maintenance and modernization. In terms of configuration, the electrical distribution network in Serbia is very similar to the networks in the European Union (EU) countries. However, there are three parameters by which Serbian electrical distribution network significantly differs:

1. The high voltage components are very old;
2. The power losses are very high;
3. The average load of the power transformers is more favorable compared to the average load of

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power transformers in the EU.

In this paper, we will analyze the financial effects of certain measures whose implementation significantly reduces electricity losses (both technical losses and losses due to unauthorized consumption).

2 Efficiency of electrical distribution networks – literature review and effects of implemented measures

When discussing the enhancement of electrical distribution network efficiency, three groups of measures are generally considered [1]:

a) **Traditional measures** (electrical distribution network reconstruction and/or reconfiguration, which involves the replacement of distribution transformers, increasing conductor cross-sections, shortening feeder lengths, and changing the voltage level). Energy losses can be significantly reduced by increasing the cross-section of overhead and underground lines, installing distribution transformers with lower copper and no-load losses, and reducing peak transformer loading.

b) **Changes in electrical distribution network management concepts** (implementation of the Smart Grid concept).

c) **Achieving flexible operation of connected distributed resources** (through incentive tariff control).

No-load losses of distribution transformers constitute a considerable share of total electrical network losses. In EU countries, transmission losses range between $(1 \div 2.6)\%$, while distribution losses range between $(2.3 \div 13.4)\%$ [2]. Typically, one-third of the total losses in the power system originate from power transformers, of which 66% are fixed losses (transformer no-load losses). The operational efficiency of power transformers depends on the load level. The utilization factor is 99.4% at a load of $(0.4 \div 0.5) \cdot S_n$. In the EU, the average loading of distribution transformers is 18.9%, with an efficiency of 98.38% [3]. Analyses show that replacing old transformers with new units would improve efficiency by 0.35% [4].

Power/distribution transformers older than 35 years should be unconditionally replaced. In the EU, 20% of the oldest transformers account for 35% of fixed losses and 30% of variable losses, corresponding to around 38 TWh annually. By replacing these transformers, losses would be reduced by approximately 30 TWh per year, which practically equals Denmark's annual electricity consumption [5].

In Ireland, rural electrical distribution network reconstruction was carried out by upgrading from a voltage level of 10 kV to 20 kV [6]. The results were as follows: the higher costs of necessary equipment replacement were negligible, voltage drops were halved, current-carrying capacity of lines was doubled, and losses were reduced by 75%.

The integration of distributed generation (DG) into the network can significantly affect loss levels. A study conducted in Switzerland demonstrated that the connection of DG to a low-voltage network, covering 25% of demand, led to a 20% reduction in losses. However, increasing DG integration to 50% had no further impact on loss reduction [7].

The implementation of reactive power compensation also has a considerable effect on reducing losses.

One of the analyzed measures involves "shifting" the peak of the load curve by flattening it through time-differentiated electricity pricing. For example, after introducing this measure in Sweden, cost reductions were achieved in the range of $(4 \div 18)\%$, equivalent to 350 000 kWh annually in energy terms, equal to the electricity consumption of 55 households [8]. In low-voltage networks, balancing phase loads has been shown to produce annual savings of 130 kWh/consumer in Russia [9]. In Belgium, a reduction in energy losses of $7 \cdot 10^6$ kWh/year was achieved [10].

In the Netherlands, 53 000 distribution transformers were installed. The replacement of 150 of the oldest units with newer units, at an average cost of 5300 EUR per transformer, resulted in a 0.1% reduction in losses [11, 12].

In Slovakia, the maximum conductor cross-section in low-voltage networks was increased from 70 mm^2 to 150 mm^2, leading to an average loss reduction of 5%.

The "decentralization of supply" has proven to be a highly effective solution. Instead of a single high-capacity transformer, multiple smaller distribution transformers are used. This extends the medium-voltage line but shortens the low-voltage network, as distribution transformers are placed as close as possible to end consumers. In this way, losses were reduced by about 47%.

Electricité de France analyzed the application of local voltage regulators to control the reactive power of distributed generators connected to the medium-voltage network. The results showed a reduction in total losses by $(2 \div 3)\%$ and overall costs by around 5%, compared to operation without reactive power control, mainly due to the deferral of network reconstruction [13–17].

3 Financial effects of measures for power loss reduction

Before we present the results of the performed analyses, we will provide some of the input data:

- The calculation was carried out for the electricity price of €0.2 per kWh (The price of electricity in EU member states varies within a very wide range. In the second half of 2024, the average price amounted to €0.287 per kWh (including all taxes and charges), while excluding taxes and charges it was around €0.215 per kWh https://ec.europa.eu/eurostat ;
- For the average annual electricity consumption, one percent of electricity losses is about $300 \cdot 10^6$ kWh/year which costs €$60 \cdot 10^6$ per year ;
- The high-voltage equipment price is assumed to be equal to the retail price of equipment from major European manufacturers;
- Reactive power compensation has not been considered, since its justification has long been proven. The investment in reactive power compensation pays off in less than a year.

Finally, regarding the configuration of the electrical distribution network in Serbia, the statistical data are as follows [18, 19]:

- Number of distribution transformer substations (TS MV/LV): about 35,000,
- Average installed capacity: 376 kVA (The adopted rating of the distribution transformers favors safety. Namely, the network is dominated by distribution transformers with ratings up to 250 kVA). Their purchase cost is significantly lower, but their copper and iron losses are not proportionally smaller compared to the corresponding values for 400 kVA distribution transformers.)
- Average load factor: $m = 0.25$,
- Total number of LV feeders: 166,000,
- Average length of LV feeders: 0.672 km,
- Average number of LV feeders per substation: 5.

3.1 Implementation of Smart Electricity Meters

By installing smart electricity meters (meters with remote reading capability), losses due to unauthorized electricity consumption are eliminated, as well as the costs of manual electricity meter reading for billing purposes. Furthermore, network management becomes easier.

In the EU, it is planned that by 2030, smart electricity meters will be installed for 92% of customers. Installation needs to be carried out for 266 million consumers, at an average price of €153.3 per meter. Installing smart electricity meters at about 2 million metering points in Serbia would cost around €300 million. If unauthorized consumption, amounting to 1% of annual consumption, were eliminated in this way, the investment would pay off in about five years, without taking into account the savings from eliminating monthly manual meter reading costs [2, 3, 20–22].

3.2 Reduction of Load and Replacement of Power Transformers

Typically, $\frac{1}{3}$ of total losses in the power system are power transformers losses, of which 66% are fixed losses (no-load losses of power transformers) [2, 3, 20–22]. The efficiency is 99.4% at a load of $(0.4 \div 0.5) \cdot S_n$.

In EU countries, the average load of power transformers in electrical distribution networks is 18.9%, with an efficiency degree of 98.38%. In Serbia, the average annual load of distribution transformers is 25%. Power transformer power losses consist of: - copper losses P_{Cu}, which depend on the load degree, and - iron losses P_{Fe}, which are independent of the load degree. At rated load S_n, copper and iron losses are $P_{\mathrm{Cu},n}$ and P_{Fe_n}, respectively. ($P_{\mathrm{Fe}} \approx P_{\mathrm{Fe}_n}$).

At a power transformer load of S, $S \neq S_n$, power transformer losses can be calculated as:

$$P_{\mathrm{loss}} = P_{\mathrm{Fe}} + P_{\mathrm{Cu},n} \left(\frac{S}{S_n} \right)^2 \tag{1}$$

The maximum load of power transformers in Serbia is 80% of rated capacity. Power and energy losses in copper for a typical transformer load curve (see Figure 1) are equal to:

$$\Delta P_{\mathrm{Cu}}(t) = \frac{P_{\mathrm{Cu},n}}{S_{nT}^2} P(t)^2 \tag{2}$$

Table 1. Iron and copper losses at rated load for conventional power transformers and power transformers with amorphous cores.

Transformer Type	Power (kVA)	Iron Losses [W]	Copper Losses [W]
Conventional distribution transformers	315	600	5350
	400	750	6000
	630	1030	8400
	1000	1350	12500
Distribution transformers with amorphous cores	315	160	3650
	400	220	3850
	630	300	5060
	1000	500	6530

$$\Delta W_{\text{Cu,year}} = \int_0^{8760} \Delta P_{\text{Cu}}(t)dt = \frac{P_{\text{Cu},n}}{S_{nT}^2} \int_0^{8760} P(t)^2 dt \quad (3)$$

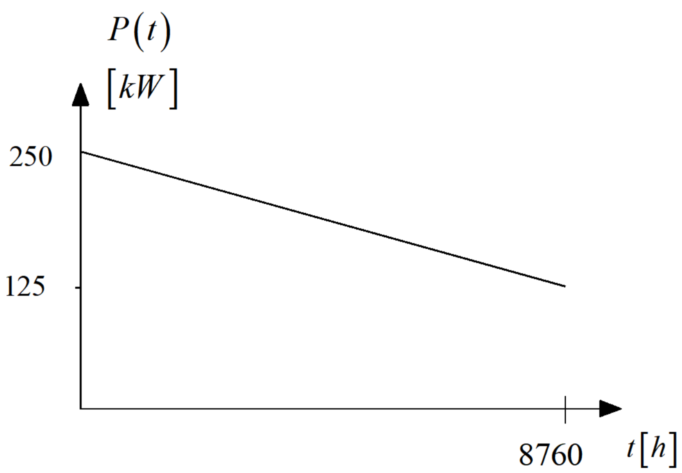

Figure 1. Linearized annual load duration curve of a distribution transformer.

Analyses have shown that it is justified to adopt the criterion applied in Germany, according to which the maximum loads of power transformers do not exceed 60% of rated capacity. Furthermore, it is economically justified to use power transformers with amorphous cores instead of conventional power transformers. Data on iron and copper losses at rated load for these transformers are given in Table 1.

3.2.1 *Replacement of existing transformers with amorphous core units*

There are about 35,000 distribution transformers in Serbia, with an average installed capacity of 376 kVA (approximately 400 kVA) and an average load factor of 0.25 [18, 19, 23, 24]. Energy losses in 35,000 power transformers are: $W_{PT,prosent} = 35,000 \cdot (0.75 + 6 \cdot 0.25^2) \cdot 8,760 = 344.925 \cdot 10^6$ kWh/year.

If this amount represents one-third of the total losses, we conclude that the total technical energy losses are 3.45%. If all existing power transformers were replaced with amorphous core units, the losses would be:

$$\begin{aligned} W_{PT,amorphous} &= 35,000 \cdot \left(0.22 + 3.85 \cdot 0.25^2\right) \cdot 8,760 \\ &= 141.227 \cdot 10^6 \text{ kWh/year} \end{aligned}$$

The annual reduction of energy losses would be:

$$\begin{aligned} \Delta W_{tranity} &= 344.925 \cdot 10^6 \text{ kWh} - 141.227 \cdot 10^6 \text{ kWh} \\ &= 203.7 \cdot 10^6 \text{ kWh.} \end{aligned}$$

One TS MV/LV with a 400 kVA amorphous core distribution transformer costs about €15,000. For the assumed electricity price of €0.2 per kWh, the simple payback period would be:

$$\frac{35{,}000 \times \text{€}\,15{,}000}{203.7 \times 10^6 \,\frac{\text{kWh}}{\text{year}} \times \text{€}\,0.2 \,\text{per kWh}} = 12.88 \text{ years}$$

Here, the residual value of equipment is neglected. (For a power transformer load factor of 0.5 the payback period would be 8 years).

3.2.2 *Replacement of existing power transformers with higher-rated units to reduce peak load from 80% to 60% of rated capacity*

The new power transformer would have an amorphous core, with a price about 30% higher than a conventional unit.

For example, suppose a 315 kVA conventional distribution transformer has a peak load of 80% (315 kVA · 0.8 = 252 kVA). This load corresponds to 63% of rated capacity for a 400 kVA unit.

- For the 315 kVA conventional distribution transformer: $P_{\text{Fe}} = 0.6\,\text{kW}$, $P_{\text{Cu},n} = 5.35\,\text{kW}$.

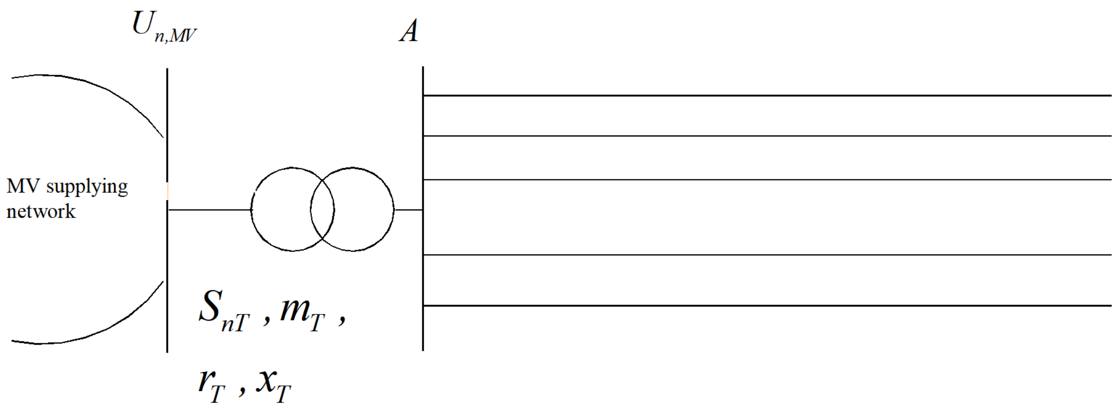

Figure 2. MV/LV substation with one distribution transformer supplying 5 LV feeders.

- For the 400 kVA amorphous core distribution transformer: $P_{\text{Fe}} = 0.22\,\text{kW}$, $P_{\text{Cu},n} = 3.85\,\text{kW}$.

For the given load curve, the annual energy losses in the 315 kVA conventional distribution transformer are 22,456 kWh.

The losses in the 400 kVA amorphous core transformer are 9,603 kWh, meaning the annual losses reduction is 12,853 kWh.

The value of annual savings is 12,853 kWh · €0.2 per kWh = €2,570.6 per year. Neglecting the residual value of the replaced unit, the payback period of this investment is

$$\frac{15,000}{2,570.6} = 5.83\,\text{years}.$$

3.3 Increasing the Cross-Section of Existing Lines

Let $I_{atr,a}$ be the tabulated value of the continuous current-carrying capacity of a conductor with cross-section a. If m is the average load factor, the annual energy losses ΔW_{loss} is equal to [20–24]:

$$\Delta W_{\text{loss}} = \frac{3 \cdot R\,(m \cdot I_{atr,a})^2 \cdot 8,760}{1,000} \left(\frac{\text{kWh}}{\text{year}}\right) \tag{4}$$

where $R[\Omega]$ is the active resistance of the conductor of given length. Analyses were carried out for aluminum conductors. If, on average, one substation supplies 5 feeders, and the load factor is $m = 0.25$, the average current per feeder is:

$$I = \frac{376,000}{5 \cdot \sqrt{3} \cdot 400} \cdot 0.25 = 27.16\,\text{A}.$$

For 166,000 feeders, each 0.672 km long, the annual energy losses are:

$$W_{\text{feeders}} = 166,000 \cdot 0.672 \cdot 8,760 \cdot 3 \cdot \frac{r \cdot 27.16^2}{1,000}\,\text{kWh}. \tag{5}$$

Assuming all feeders have the same cross-section and are made of aluminum cables, the losses for different conductor cross-sections and the total losses are shown in Table 2. From the data in Table 2 and the retail prices of cables, simple payback periods for replacing existing cables with larger cross-sections were calculated (Table 3).

Table 2. Annual losses in feeders and total losses (sum of line and transformer losses).

Cross section of the feeder conductor (mm^2)	W_{feeders}, 10^6 kWh	$W_{\text{feeders}}+W_{PT,\text{present}}$, %
35	2,249.01	8.64
50	1,665.14	6.70
70	1,152.62	4.99
95	832.57	3.92
120	659.57	3.35
150	536.30	2.94

Table 3. Simple payback periods for replacing existing cables with larger cross-section conductors (1 km cable costs € (5,000–15,000) and primarily depends on the cross-sectional area).

Existing conductor cross-section (mm^2)	Payback period (years) for replacement with conductor cross-section (mm^2)				
	50	70	95	120	150
35	5.8	3.8	4.0	4.5	4.8
50	–	8.2	6.8	7.1	7.3
70	–	–	17.7	14.4	13.6
95	–	–	–	41.0	27.8
120	–	–	–	–	66.8

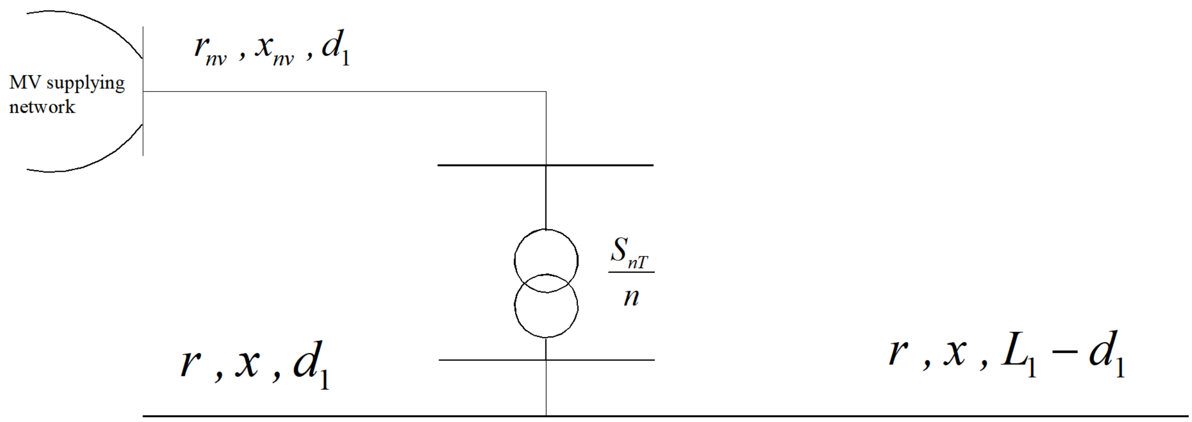

Figure 3. Proposed configuration: "one LV feeder – one distribution transformer".

3.4 Shortening LV feeders by extending MV feeders and replacing existing distribution transformers

Currently, one substation (average installed capacity 376 kVA) supplies 5 feeders of average length 0.672 km (Figure 2) [21–24].

For the current configuration (Figure 2), the annual losses per substation (one power transformer + 5 feeders) are:

$$\begin{aligned} W_{1T+5\,\text{feeder}} &= 8,760 \cdot \left(0.75 + 6 \cdot 0.25^2\right) \\ &+ 5 \cdot 0.672 \cdot 3 \cdot \frac{r \cdot 27.16^2}{1,000} \cdot 8,760 \\ &= 9,855 + 65,136.46 \cdot r, \frac{\text{kWh}}{\text{year}} \end{aligned} \quad (6)$$

Now let us analyze the following configuration: Instead of supplying the n LV feeders from a single power transformer with rated power S_{nT}, we shall assume that each feeder is supplied from a transformer substation equipped with a distribution transformer of rated power S_{nT}/n with the substation located at the midpoint of the feeder. Therefore, instead of the configuration shown in Figure 2, we propose that, on average, each feeder is supplied by a single distribution transformer with an amorphous core, rated at 80 kVA, with the transformer substation located approximately at the midpoint of the feeder, as shown in Figure 3.

The losses for 5 such substations (each with one transformer and 5 halved feeders) are:

$$\begin{aligned} W_{5PT+5\,\text{halved feeders}} &= 5 \cdot 8,760 \cdot (0.06 + 1.125 \cdot 0.235^2) \\ &+ 10 \cdot \frac{0.672}{2} \cdot 3 \cdot \frac{r \cdot 13.58^2}{1,000} \cdot 8,760 \\ &= 5,349.21 + 16,284.12 \cdot r, \frac{\text{kWh}}{\text{year}} \end{aligned} \quad (7)$$

The results for different conductor cross-sections are shown in Table 4.

Table 4. Power losses for the configuration in Figure 2 and Figure 3 and annual savings depending on feeder conductor cross-section.

Cross section of the feeder conductor, mm^2	$W_{1PT+5\,\text{feeders}}$ (kWh)	$W_{5PT+5\,\text{halved feeders}}$ (kWh)	Annual savings, €
35	77,597	22,285	11,062
50	60,010	17,888	8,424
70	44,572	14,029	6,108
95	34,932	11,618	4,663
120	29,721	10,315	3,881
150	26,009	9,388	3,324

If applied to all 35,000 transformer substations, the annual savings because of losses reduction would be € $(116.3 \div 387.2) \cdot 10^6$. It is important to note that the extension of the medium-voltage network entails increased investment costs due to property and legal considerations.

4 Conclusion

If the analyzed measures were implemented, together with the compensation of the no-load reactive power of distribution transformers, the total investment would amount to approximately 4.77 billion euros. The largest share of this investment would relate to the reconstruction of the low-voltage network—about 2.4 billion euros—which includes increasing the cross-sectional area of conductors along approximately

120,000 kilometers of the network. The reconstruction and extension of the 10 kV medium-voltage network, covering around 60,000 kilometers, would require an additional 1.5 billion euros.

The procurement and installation of 35,000 MV/LV substations, each equipped with a distribution transformer with an amorphous core, would represent an investment of about 525 million euros, while the installation of two million smart energy meters would add another 300 million euros. Finally, the compensation of the no-load reactive power for 35,000 distribution transformers would require approximately 17.5 million euros.

When the effects of the analyzed measures and their implementation costs are taken into account, with an electricity price of €0.2 per kWh, the investment payback period would be 7–8 years. Even if the price of electricity were lower, it is evident that the analyzed measures would still be cost-effective over a reasonably longer period of time. Considering that the implementation of the mentioned measures would reduce power losses by about 15% annually, production capacities of approximately 1,000 MW would be released. This provides additional justification for implementing all the analyzed measures.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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