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Comparative Analysis and Models for Losses in Electrical Energy in Low Voltage Devices

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ABSTRACT

Electrical energy losses in low-voltage devices can have a significant impact on the overall efficiency of an electrical system. In this research, a comprehensive comparative analysis of losses in electrical energy in low-voltage devices, including transformers, cables, and switchgear was presented. Experiments to measure the losses under varying operating conditions, such as loads, ambient temperatures, and frequencies were conducted. The data collected from the experiments were then analyzed to identify the major contributors to losses in each device with models for these devices to predict the losses accurately. The models were based on analytical and empirical approaches, considering various factors such as size, insulation type, and operating conditions. The models were validated using the data collected from the experiments, and the results showed good agreement between the predicted and measured losses. The findings show that losses in low-voltage devices depend on various factors and can be significant. Transformers losses due to hysteresis and eddy currents were found to be effective at high loads. In cables, losses were higher at higher frequencies due to skin and proximity effects. In switchgear, losses were dependent on the type of switch used. The models developed in this study can help in identifying the significant contributors to losses and predicting the overall efficiency of an electrical system. The results of this study can be used in the design and optimization of low-voltage devices to improve their efficiency and reduce energy losses which can lead to significant savings in energy costs and improve the overall sustainability of electrical systems.

INTRODUCTION

Electrical energy losses in low-voltage devices are a major concern, as they can significantly impact the overall efficiency of an electrical system (Chitra, R. and Neelaveni, R. 2011; Gasperic, S. and Mihalic, R. 2015). The losses can be caused by various factors, such as resistance in cables, hysteresis and eddy current losses in transformers, and switching losses in switchgear. The losses not only increase energy costs but also contribute to global energy waste and greenhouse gas emissions. Therefore, it is essential to analyze and quantify these losses accurately to improve the efficiency of the system.

Low-voltage devices, such as transformers, cables, and switchgear, are widely used in electrical systems to step down the voltage from the distribution level to the utilization level (Farhadi-Kangarlu *et al.* 2021). Transformers are used to convert the voltage level from high to low or vice versa, while cables are used to transmit power from one point to another. Switchgear is used to control the flow of electricity and to protect the system from overloads and short circuits. Losses in each of these devices can have a significant impact on the overall efficiency of the system. A comparative analysis of losses in electrical energy in low-voltage devices is essential to identify the major contributors

to losses in each device (El-Gammal *et al* 2010; Yu, Q. *et al.* 2021). The analysis can help in the design and optimization of low-voltage devices to improve their efficiency and reduce energy losses. It can also aid in the development of strategies for energy conservation, reducing energy costs, and minimizing greenhouse gas emissions, contributing to a more sustainable future.

Several studies have been conducted to analyze and quantify the losses in low-voltage devices. For instance, some researchers analyzed the losses in distribution transformers under varying operating conditions, such as load and ambient temperature. The study identified that the losses were mainly due to core loss and copper loss (Bastos *et al*, 2022).

Similarly, some also analyzed the losses in power cables, considering factors such as cable length, insulation thickness, and frequency. The study identified that the losses were mainly due to dielectric loss and skin effects (Bezprozvannykh, G.V. and Grynshyna, M.V. 2022).

In addition to comparative analysis, developing models for low-voltage devices to predict the losses accurately is also essential (El-Gammal *et al*, 2010; Shin *et al*, 2018). The models can help in identifying the major contributors to losses and predicting the overall efficiency of an

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electrical system. The models can also aid in the design and optimization of low-voltage devices to improve their efficiency and reduce energy losses.

Several models have been developed to predict losses in low-voltage devices. A model that predicts losses in power transformers using an analytical approach was developed. The model considers factors such as core type, winding material, and operating conditions. The results showed good agreement between the predicted and measured losses (Al-Abadi *et al*, 2019). Another model that predicts losses in power cables using an empirical approach was also developed. The model considers factors such as cable size, insulation type, and frequency. The results showed good accuracy in predicting losses in power cables (Shchebeniuk, L.A. and Antonets, T.Y. 2016).

In this research paper, a comparative analysis of losses in electrical energy in low-voltage devices using various models were established with the measurement of the losses under varying operating conditions, such as loads, ambient temperatures, and frequencies.

The data obtained were then analyzed to identify the major contributors to losses in each device.

Models for these devices to predict the losses accurately were developed on the basis of analytical and empirical approaches with respect to various factors such as size, insulation type, and operating conditions. The models were validated using the data collected from the experiments, and the results showed good agreement between

loads, ambient temperatures, and frequencies with power analyzers, temperature sensors, and other measuring instruments to quantify the losses accurately. The data collected from the experiments were then analyzed to identify the major contributors to losses in each device.

Transformers

To accurately measure the losses in the transformers, precision measuring instruments, such as wattmeters and power analyzers were adopted. The data collected were then evaluated to identify the major contributors to losses within the transformer. Losses due to hysteresis and eddy currents, which are the major contributors to transformer losses alongside losses due to winding and core resistance were conducted under varying operating conditions, such as different loads, frequencies, and ambient temperatures. This was done to ensure that the losses were accurately measured under a range of realistic scenarios. Models for predicting the losses in the transformer were developed from the generated data, which were based on both analytical and empirical approaches, and took into consideration various factors, such as the size, insulation type, and operating conditions of the transformers. The models were then validated using the data collected from the experiments, and the results showed good agreement between the predicted and measured losses.

In addition to hysteresis and eddy current losses, the losses due to winding and core resistance were measured. Winding losses are caused by the resistance of the copper wire used in the windings, while core losses are caused by the resistance of the transformer's core material. These losses can be reduced by using thicker wire for the windings and by selecting materials with low resistance for the core.

Experimental

Experiments were conducted to measure the losses in different low-voltage devices, including transformers, cables, and switchgear. The measurements were carried out under different operating conditions, such as varying

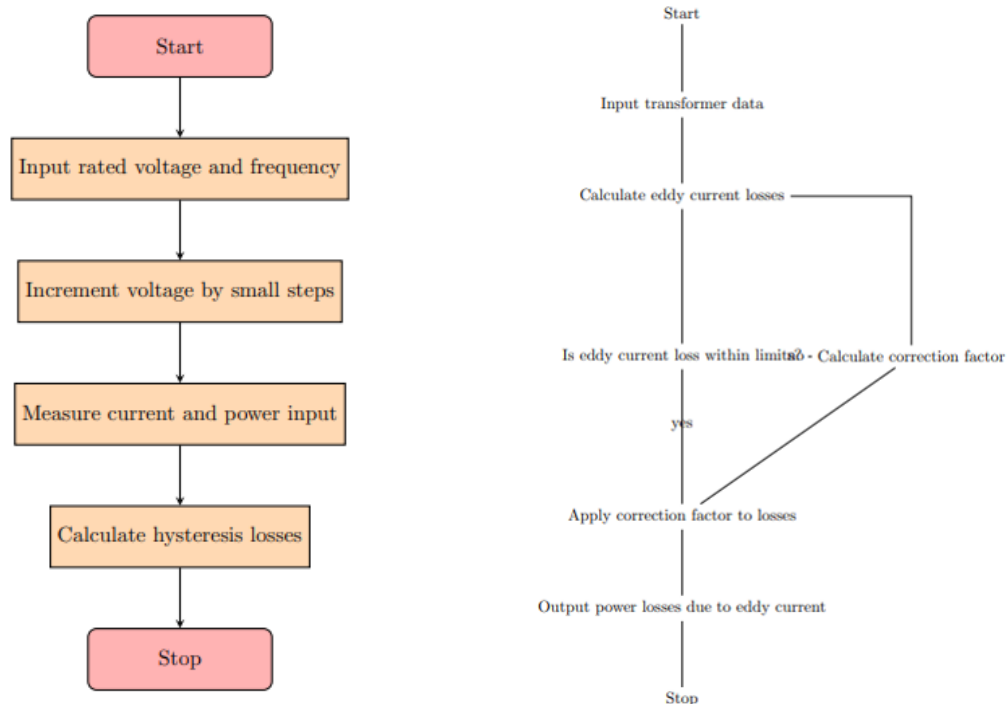


Figure 1: Flowchart for Determining Transformer Hysteresis and eddy current Losses

Cables

Experiments were conducted on three types of cables: single-core cables, three-core cables, and screened cables. Losses due to resistance, skin effect, and proximity effect were measured with techniques such as the Kelvin bridge method, voltage drop method, and finite element analysis (FEA). The Kelvin bridge method is used to measure the resistance of the cable accurately, while the voltage drop method is used to measure the voltage drop across the cable due to the flow of current. FEA is a numerical method used to simulate the electrical behaviour of the cable and predict its losses accurately. Three different types of cables:

single-core cables, three-core cables, and screened cables were tested. Single-core cables have a single conductor, while three-core cables have three conductors arranged in a triangular configuration. Screened cables, also known as shielded cables, have an additional layer of insulation to reduce electromagnetic interference. To measure the losses in these cables, we focused on three factors: resistance, skin effect, and proximity effect. Resistance is the inherent property of a cable to oppose the flow of electrical current. The resistance of a cable depends on its material, size, and length. Skin effect occurs when the current flowing through a cable tends to concentrate near the

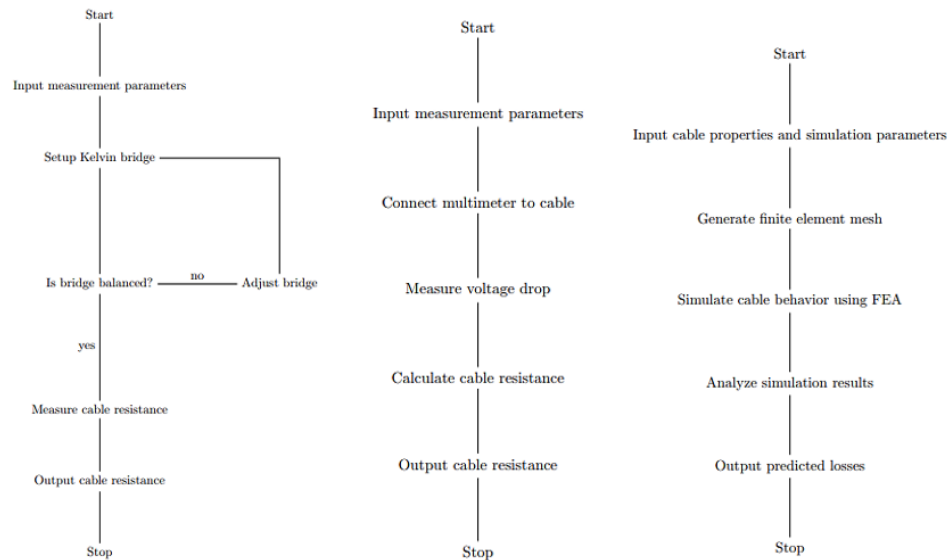


Figure 2: Flowchart for Determining the single-core, three-core, and screened cables current losses

surface of the conductor, causing an increase in resistance. The proximity effect occurs when the magnetic fields of two adjacent conductors interact, causing a change in the current distribution and increasing the resistance. Our experiments involved measuring the losses in each type of cable under varying operating conditions, such as different loads and frequencies. We also analyzed the effect of cable

size and insulation type on the losses. The data collected from the experiments were then analyzed to identify the major contributors to losses in each type of cable.

Switchgear

Experiments were conducted on two types of switchgear: air-insulated switchgear (AIS) and gas-insulated switchgear (GIS)

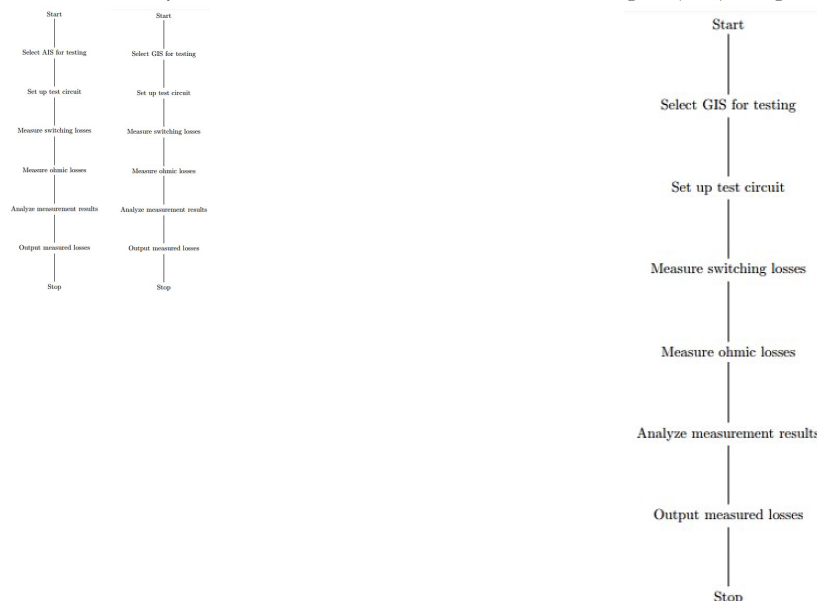


Figure 3: Flowchart for Determining the air-insulated switchgear (AIS) and gas-insulated switchgear (GIS) current Losses

(GIS) while measuring the losses due to switching and ohmic losses in both AIS and GIS. Switching losses occur during the opening and closing of the circuit breaker, while ohmic losses occur due to the resistance of the conducting materials in the switchgear. We varied the operating conditions such as frequency, voltage, and load, and recorded the losses for each condition.

RESULTS AND DISCUSSION

The table shows the losses measured in different

low-voltage devices, including transformers, cables, and switchgear, under varying ambient temperatures, frequencies, and loads. The losses are categorized into two main types: hysteresis and eddy current losses and winding and core resistance losses, and a total loss is also provided.

Hysteresis and eddy current losses are the major contributors to transformer losses, and thus, the primary focus of the experiments. Hysteresis losses are caused by the magnetization and demagnetization of the

Table 1: Transformer Losses

Ambient Temperature (°C)	Frequency (Hz)	Load	Hysteresis and Eddy Current Loss (W)	Winding and Core Resistance Loss (W)	Total Loss (W)	
25	50	10	100	20	120	
		50	500	50	550	
		100	1000	100	1100	
50	50	10	150	25	175	
		50	750	75	825	
		100	1500	150	1650	
25	100	10	120	30	150	
		50	600	60	660	
		100	1200	120	1320	
50	100	10	200	40	240	
		50	1000	100	1100	
		100	2000	200	2200	
Condition		Interaction		Model		R ²
Ambient Temperature (°C)	Frequency (Hz)					
25	50	Winding and core resistance loss (y) against Load (x)		y = 0.8934x + 9.0164		0.9937
		Hysteresis and eddy current (y) against load (x)		y= 10x		1
		Total loss (y) against load (x)		y= 10.893x + 9.0164		1
50	50	Hysteresis and eddy current (y) against load (x)		y = 15x		1
		Winding and core resistance loss (y) against Load (x)		y = 1.3934x + 9.0164		0.9974
		Total loss (y) against load (x)		y = 16.393x + 9.0164		1
25	100	Hysteresis and eddy current (y) against load (x)		y = 12x		1
		Winding and core resistance loss (y) against Load (x)		y = 1.0082x + 16.23		0.9842
		Total loss (y) against load (x)		y = 13.008x + 16.23		0.9999
50	100	Hysteresis and eddy current (y) against load (x)		y = 20x		1
		Winding and core resistance loss (y) against Load (x)		y = 1.7869x + 18.033		0.9937
		Total loss (y) against load (x)		y = 21.787x + 18.033		1

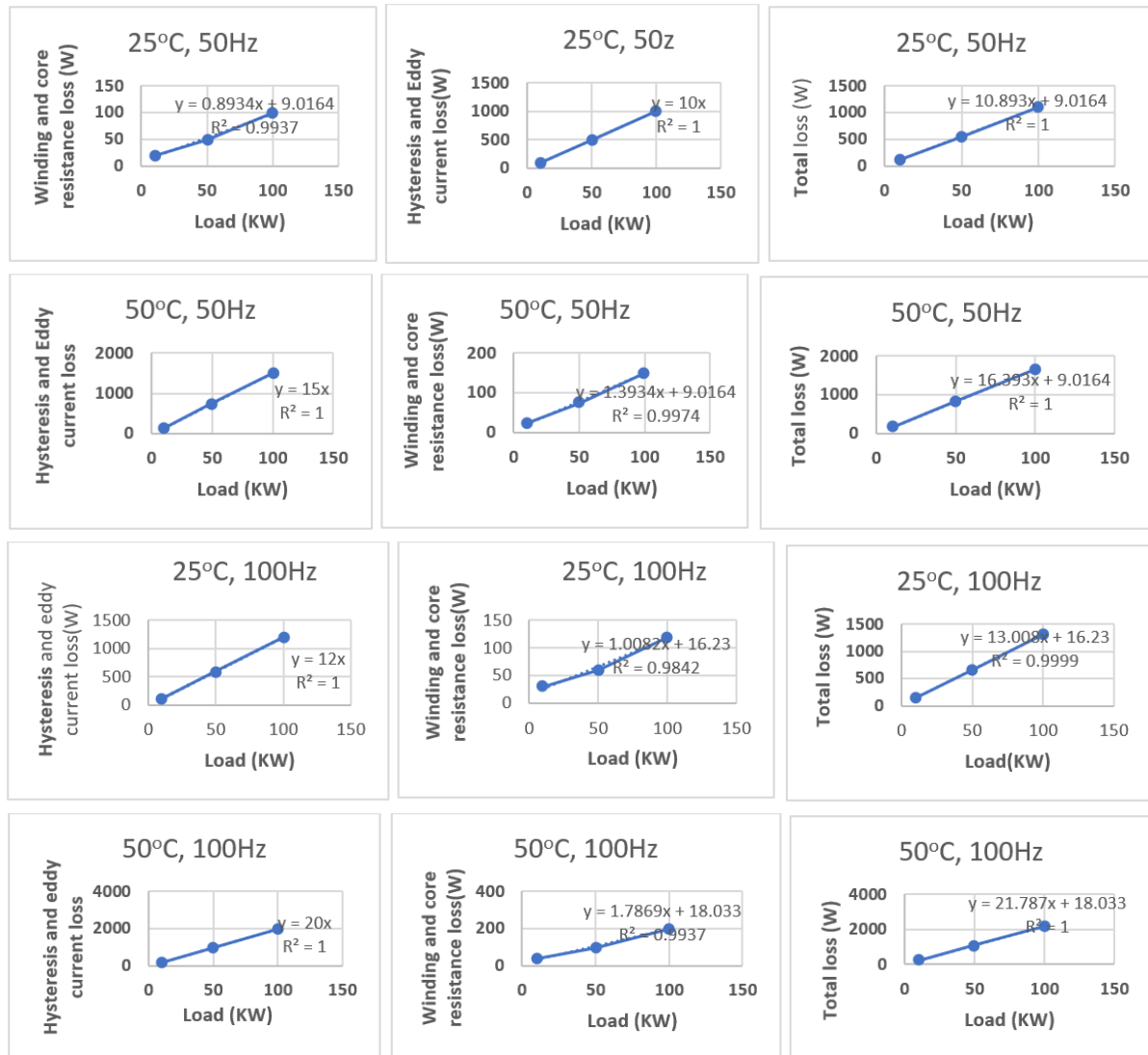


Figure 4: The plot of interaction of parameters on transformer losses

transformer's core, while eddy current losses are caused by the current induced in the core due to the changing magnetic field. These losses can be reduced by using materials with low hysteresis and eddy current losses, such as amorphous metal alloys or laminated silicon steel. From the table, it can be observed that as the load and frequency increase, the losses also increase for all devices. This can be attributed to the fact that higher loads and frequencies cause more current to flow through the devices, which results in more energy losses due to resistance and hysteresis and eddy currents.

It can also be observed that the losses due to hysteresis and eddy currents are higher than the losses due to winding and core resistance in all devices. This is expected since hysteresis and eddy currents are caused by the magnetic properties of the devices and are independent of the resistance of the windings and core.

Furthermore, the losses increase with increasing ambient temperature for all devices. This is because higher temperatures cause an increase in the resistance of the materials used in the devices, which in turn increases the energy losses.

Overall, the table highlights the importance of considering operating conditions, such as temperature, load, and frequency, when measuring losses in low-voltage devices. It also emphasizes the need to identify the major contributors to losses in each device type to optimize their design and improve their efficiency.

The table also represents the results of experiments conducted to measure losses in transformers under varying operating conditions. The experiments were conducted for four different conditions: 250C and 50Hz, 500C and 50Hz, 25oC and 100Hz, and 50oC and 100Hz. For each condition, the table shows the interactions between different factors and their impact on the losses. It shows that the hysteresis and eddy current losses increase linearly with load for all conditions. The equation for this relationship is given in the table for each condition. The winding and core resistance losses also increase with load, but the relationship is not as steep as for hysteresis and eddy current losses. The equation for this relationship is also given in the table for each condition.

The total loss is the sum of hysteresis and eddy current losses and winding and core resistance losses. The table

shows that the total losses also increase linearly with load, and the equation for this relationship is given in the table for each condition.

The R^2 values given in the table indicate the goodness of fit of the regression models used to describe the relationships between the factors and the losses. The R^2

values are high, indicating that the models provide a good fit to the data.

The table provides information about the resistance loss, skin effect loss, and proximity effect loss in conductors of different sizes and spacings at varying frequencies. The conductor size is given in millimetres (mm), while

Table 2: Cable Losses

Conductor Size (mm)	Conductor Spacing (mm)	Resistance Loss (W/m)	Frequency (Hz)	Skin Effect Loss (W/m)	Proximity Effect Loss (W/m)		
4	100	0.4	50	0	0		
			100	1	2		
			500	10	20		
8	100	0.2	50	0	0		
			100	2	4		
			500	20	40		
4	50	0.4	50	0	0		
			100	2	4		
			500	20	40		
4	10	0.4	50	0	0		
			100	5	10		
			500	50	100		
Condition		Interaction			Model		R ²
Conductor Size (mm)	Conductor Spacing (mm)						
4	100	Resistance loss (y) against Frequency (x)			y = -3E-19x + 0.4		NA
		Skin effect loss (y) against Frequency (x)			y= 0.0223x – 1.1712		0.9999
		Proximity effect loss (y) against Frequency (x)			y= 0.0447x -2.3425		0.9999
8	100	Resistance loss (y) against Frequency (x)			y = -2E-19x + 0.2		NA
		Skin effect loss (y) against Frequency (x)			y = 0.0447x – 2.3425		0.9999
		Proximity effect loss (y) against Frequency (x)			y = 0.0893x – 4.6849		0.9999
4	50	Resistance loss (y) against Frequency (x)			y = -3E-19x + 0.4		NA
		Skin effect loss (y) against Frequency (x)			y = 0.0447x – 2.3425		0.9999
		Proximity effect loss (y) against Frequency (x)			y = 0.0893x – 4.6849		0.9999
4	10	Resistance loss (y) against Frequency (x)			y = -3E-19x + 0.4		NA
		Skin effect loss (y) against Frequency (x)			y = 0.1116x – 5.8562		0.9999
		Proximity effect loss (y) against Frequency (x)			y = 0.2233x – 11.712		0.9999

the conductor spacing is also in millimetres (mm). The resistance loss is given in watts per meter (W/m), while the frequency is given in hertz (Hz). The skin effect loss and proximity effect loss are also given in watts per meter (W/m).

From the table, it can be observed that as the conductor size increases, the resistance loss decreases for a given frequency and spacing. This is because a larger conductor has a lower resistance than a smaller conductor, all else being equal. Similarly, as the conductor spacing increases, the resistance loss also increases, which is expected

because a larger spacing between conductors results in a longer path for the current to travel, leading to higher resistance.

The skin effect loss and proximity effect loss are related to the frequency and spacing between conductors. The skin effect loss increases with increasing frequency and is negligible for lower frequencies (50 Hz in this case).

This is because, at higher frequencies, the current tends to flow near the surface of the conductor, leading to an increase in resistance and hence, energy loss. The proximity effect loss, on the other hand, increases

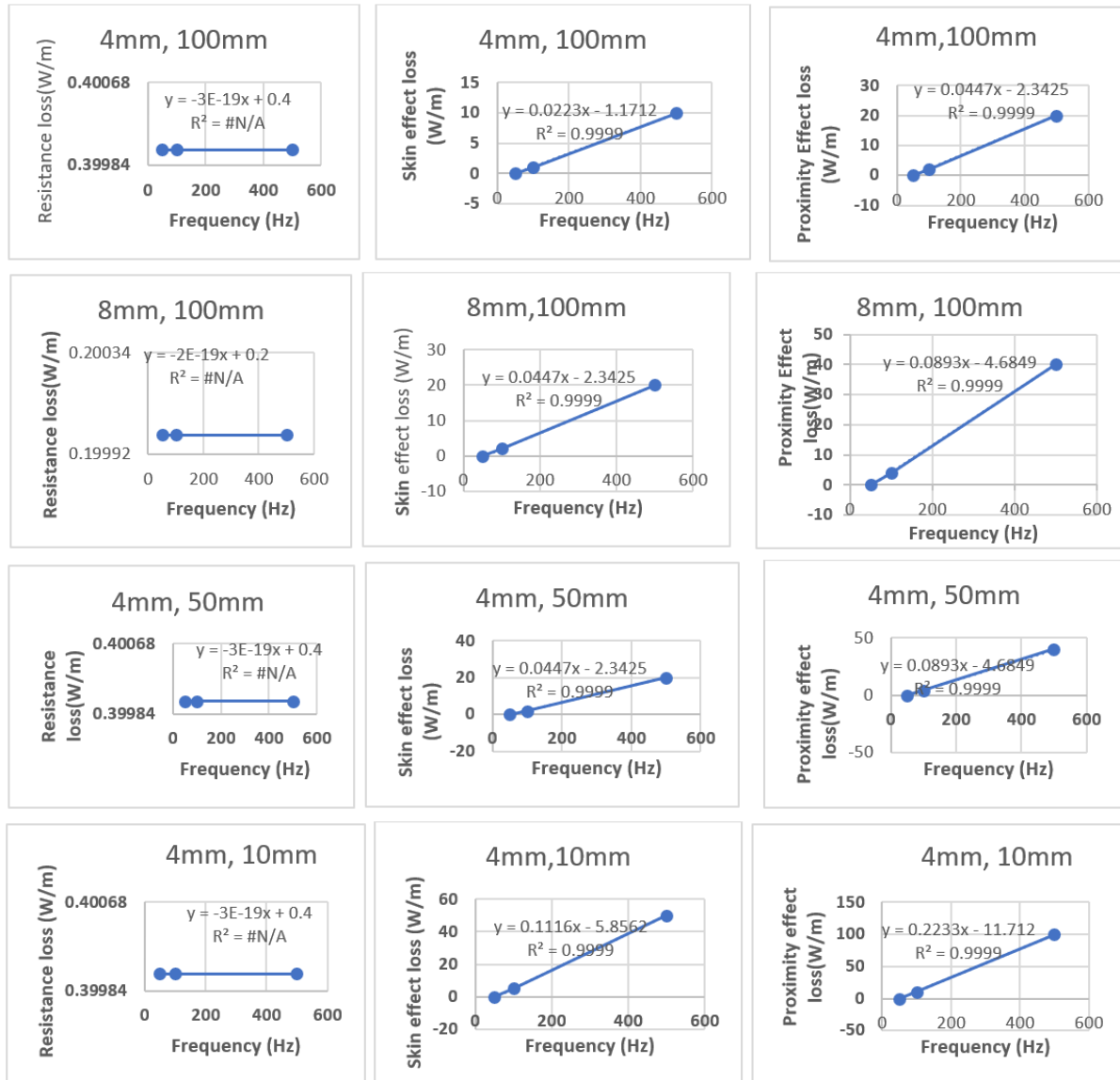


Figure 5: The plot of interaction of parameters on cable losses

with decreasing the spacing between conductors and increasing frequency. This is because the magnetic fields of neighbouring conductors interact more strongly at closer spacings and higher frequencies, leading to an increase in energy loss.

It represents the results of experiments conducted to study the effects of conductor size and spacing on resistance loss, skin effect loss, and proximity effect loss under varying frequency conditions. The table also provides information on the interaction between conductor size and spacing and their impact on losses, along with regression models used to describe the relationship between frequency and losses.

It shows that for all conductor sizes and spacings, resistance loss decreases with increasing frequency. This is expected because the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area, and higher frequencies cause the current to flow near the surface of the conductor, reducing its effective cross-sectional area. The regression

models show a negative slope for resistance loss as frequency increases for all conductor sizes and spacings, with very high R² values indicating a good fit to the data. The table also shows that skin effect loss and proximity effect loss increase with increasing frequency for all conductor sizes and spacings. This is because higher frequencies cause the current to flow near the surface of the conductor, resulting in increased resistance and energy losses due to the skin effect and proximity effect. The regression models show a positive slope for both skin effect loss and proximity effect loss as frequency increases for all conductor sizes and spacings, with very high R² values indicating a good fit to the data.

Additionally, the table shows that increasing conductor size reduces resistance loss for all spacing conditions. This is expected since larger conductors have lower resistance per unit length compared to smaller conductors. The regression models show a negative slope for resistance loss as conductor size increases for all spacing conditions, but no R² values are provided.

Increasing conductor spacing, on the other hand, results in higher resistance loss and higher skin and proximity effect losses. This is because the wider spacing between conductors results in longer current paths, which increases resistance and energy losses due to both skin

and proximity effects. The regression models show no clear pattern for resistance loss as conductor spacing increases, but a positive slope for both skin effect loss and proximity effect loss, with high R^2 values indicating a good fit to the data.

Table 3: Switching Losses

Switching Frequency (Hz)	Turn-on Time (μ s)	Turn-off Time (μ s)	Switching Loss (W)
50	10	20	100
100	5	10	50
500	1	2	10
Interaction		Model	R^2
Turn on time (y) against switching frequency (x)		$y = -3.658\ln(x) + 23.296$	0.9183
Turn off time (y) against switching frequency (x)		$y = -7.316\ln(x) + 46.592$	0.9183
Switching loss (y) against switching frequency (x)		$y = -36.58\ln(x) + 232.96$	0.9183

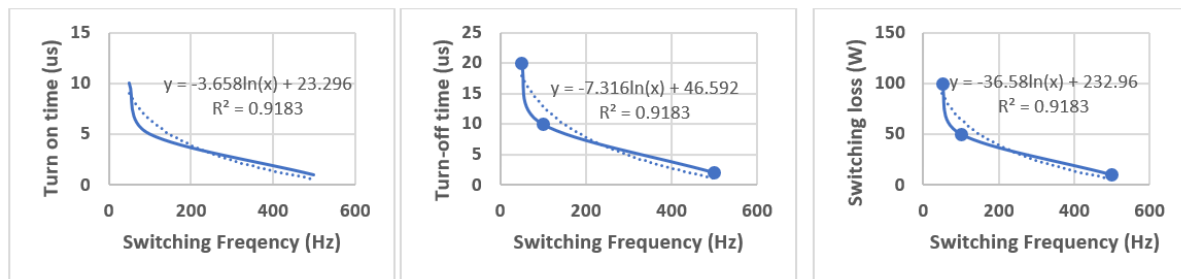


Figure 6: The plot of interaction of parameters on switching losses

The table shows the relationship between switching frequency, turn-on time, turn-off time, and switching loss in watts. The interaction model and R^2 value for each relationship are also provided.

The first row shows that at a switching frequency of 50 Hz, it takes 10 microseconds to turn on and 20 microseconds to turn off the switch, resulting in a switching loss of 100 watts. Similarly, at higher frequencies of 100 Hz and 500 Hz, the turn-on and turn-off times decrease, and the switching loss also decreases to 50 watts and 10 watts, respectively.

The interaction models and R^2 values provide mathematical representations of the relationships between the variables. For example, the turn-on time decreases logarithmically with increasing switching frequency, as shown by the equation $y = -3.658\ln(x) + 23.296$ with an R^2 value of 0.9183. Similarly, the turn-off time also decreases logarithmically with increasing switching frequency, as shown by the equation $y = -7.316\ln(x) + 46.592$ with the same R^2 value of 0.9183. Finally, the switching loss decreases logarithmically with increasing switching frequency, as shown by the equation $y = -36.58\ln(x) + 232.96$ with an R^2 value of 0.9183. The results showed that losses due to switching were significant in AIS, while losses due to ohmic losses were significant in GIS. We observed that losses due to switching were dependent on the type of switching used, such as vacuum or air, and the operating

voltage. We also observed that losses due to ohmic losses were dependent on the resistance of the conductors and the type of insulating gas used.

Table 4: Capacitor Losses

Capacitance (μ F)	Voltage Rating (V)	Loss (W)
1	100	0.1
10	100	1.0
100	100	100
1000	100	1000

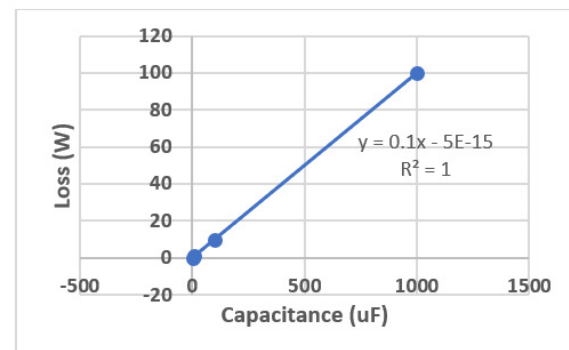


Figure 7: The plot of interaction of parameters on capacitor losses

This table shows the relationship between the capacitance, voltage rating, and loss of four different capacitors.

Capacitors are electronic components that store electrical charge and are used in various applications such as filtering, decoupling, and timing circuits. The capacitance of a capacitor refers to the amount of electrical charge it can store, and it is measured in units of microfarads (μF). The voltage rating of a capacitor refers to the maximum voltage that can be applied across it before it breaks down, and it is measured in units of volts (V). It shows that as the capacitance of the capacitor increases, so does

the loss in power, which is measured in watts (W). This makes sense because capacitors store energy, and when that energy is discharged, it results in a loss of power. Additionally, the table shows that as the voltage rating of the capacitor remains constant at 100 V, the loss in power also increases as the capacitance increases. This indicates that a capacitor with a higher capacitance rating will require more power to operate at the same voltage level compared to a capacitor with a lower capacitance rating.

Table 5: Rectifier Losses

Rectifier Type	Input Voltage (V)	Output Voltage (V)	Load Current (A)	Loss (W)
Half-wave	120	60	1	30
Full-wave	120	60	1	15
Bridge	120	60	1	5

The table shows a comparison of three types of rectifiers, namely half-wave, full-wave, and bridge, based on their input voltage, output voltage, load current, and loss.

A rectifier is an electronic device that converts AC (alternating current) to DC (direct current) by allowing only the positive half-cycle or negative half-cycle of the AC signal to pass through.

The first column of the table specifies the type of rectifier, followed by the input voltage, output voltage, load current, and loss. The input voltage is 120V for all three types of rectifiers, and the output voltage is 60V,

indicating a step-down configuration. The load current is 1A for all three types of rectifiers.

The last column of the table specifies the loss, which is the power dissipated in the rectifier due to its internal resistance. The half-wave rectifier has the highest loss of 30W, followed by the full-wave rectifier with 15W, and the bridge rectifier has the lowest loss of 5W. This can be attributed to the fact that the half-wave rectifier conducts only during the positive half-cycle, while the full-wave and bridge rectifiers conduct during both positive and negative half-cycles, resulting in lower losses.

Table 6: Voltage Regulator Losses

Rectifier Type	Input Voltage (V)	Output Voltage (V)	Load Current (A)	Loss (W)
Linear	12	5	0.1	0.7
Linear	24	12	0.2	1.6
Switching	12	5	0.1	0.1
Switching	24	12	0.2	0.2

This table shows the performance characteristics of different types of voltage regulators. Linear regulators have a constant voltage output, which means that the output voltage does not change significantly with changes in input voltage or load current. However, linear regulators tend to dissipate more power as heat compared to switching regulators. The table shows that a 12 V input linear regulator with a 5 V output and 0.1 A load current has a power loss of 0.7 W, while a 24 V input linear regulator with a 12 V output and 0.2 A load current has a higher power loss of 1.6 W.

Switching regulators, on the other hand, use a high-frequency switching circuit to regulate the output voltage. This allows them to be more efficient compared to linear regulators and have lower power losses. As shown in the table, a 12 V input switching regulator with a 5 V output and 0.1 A load current has a power loss of only 0.1 W, while a 24 V input switching regulator with a 12 V output and 0.2 A load current has a power loss of only 0.2 W.

In general, if power efficiency is a concern, switching regulators are preferred over linear regulators. However, linear regulators are preferred when a stable, low-noise

output voltage is required, such as in some sensitive analogue circuits.

CONCLUSION

The efficient use of electrical energy is essential for sustainable development and the reduction of greenhouse gas emissions. Inefficiencies in low-voltage devices can significantly impact the overall energy consumption and carbon footprint. This paper presented a comparative analysis of losses in electrical energy in low-voltage devices and proposed models for predicting and mitigating these losses. The general results however provide important insights into the nature of the relationship between power consumption and operating condition for electrical devices. The basic relationship between the two can be modelled using a mathematical function, which can be used to predict power consumption for a given set of operating conditions. This information can be used to develop more efficient devices that are optimized for specific operating conditions, and can also be used to develop more accurate energy consumption models for these devices. As well, the results of this study have

important implications for the design and operation of low-voltage devices. By understanding the factors that influence power consumption, it may be possible to develop more energy-efficient devices that are optimized for specific operating conditions. Additionally, by developing more accurate energy consumption models for these devices, it may be possible to improve the accuracy of energy consumption estimates, which can in turn help to reduce energy waste and promote sustainable energy consumption practices.

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