Overcurrent effects on copper insulated PVC cables and fire resistance via thermal imaging and macrostructure analysis

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ABSTRACT

This study investigates the effects of overcurrent on copper (Cu) insulated polyvinyl chloride (PVC) cables, focusing on their thermal behavior and fire resistance. We utilized thermal imaging, macrostructural analysis, and Joule heating calculations to evaluate six cable samples subjected to various currents. Results showed that with increasing current, the temperature of the cables rose significantly. For example, the CC0 sample, with no current, had a temperature of 36 °C, while the CC110 sample, subjected to 110 A, reached 1,091 °C. Joule heating calculations indicated energy values ranging from 0 J for the CC0 sample to 7,260,000 J for the CC110 sample. Physical observations included minor deformations at 253 °C and complete insulation loss at 1,091 °C. These findings emphasize the critical need for managing overcurrent to prevent severe cable damage and enhance system safety. This research provides practical insights for optimizing cable design and improving thermal management, offering valuable contributions to electrical engineering practices.

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1. INTRODUCTION

Electrical cables are the lifelines of modern society, serving as the conduits through which electricity flows to power a vast array of devices and systems [1]. From powering homes and businesses to enabling communication networks, and transportation infrastructure, electrical cables play a crucial role in virtually every aspect of daily life [2]. The reliability and safety of electrical systems hinge upon the integrity of these cables, making their design and construction paramount in ensuring uninterrupted power supply and mitigating potential hazards. Among the various types of electrical cables utilized in industries worldwide, those insulated with copper (Cu) and polyvinyl chloride (PVC) stand out for their widespread adoption and favorable properties [3]. Cu, prized for its high electrical conductivity and corrosion resistance, serves as the primary conductor in many electrical cables, enabling efficient transmission of electrical currents over long distances with minimal losses. Meanwhile, PVC insulation offers excellent dielectric properties [4], thermal stability [5], and resistance to moisture and chemicals [6], making it an ideal choice for protecting the Cu conductor from environmental factors and mechanical damage.

The combination of Cu conductors and PVC insulation has become ubiquitous in the electrical industry, finding applications in power distribution networks, building wiring systems, automotive wiring harnesses, and numerous other fields. The popularity of Cu insulated PVC cables stems from their versatility, reliability, and cost-effectiveness, making them the preferred choice for engineers and electricians alike [7]. Whether in residential, commercial, or industrial settings, these cables provide a dependable means of transmitting electricity [8] while adhering to stringent safety standards and regulatory requirements.

In addition to their functional attributes, Cu insulated PVC cables offer several practical advantages that contribute to their widespread adoption. Their flexibility and ease of installation [9] make them well-suited for a variety of wiring configurations, facilitating efficient deployment in diverse environments. Furthermore, their durability and resistance to abrasion and mechanical stress ensure long-term performance and reliability, even in demanding operating conditions. As such, Cu insulated PVC cables have emerged as the backbone of modern electrical infrastructure, underpinning the seamless operation of countless systems and contributing to the advancement of technology and society at large.

Overcurrent situations, characterized by excessive electrical current flowing through cables beyond their rated capacity, can lead to elevated temperatures within the cable structure [10]. This thermal stress can degrade the PVC insulation [11] and compromise the integrity of the Cu conductor, increasing the likelihood of insulation breakdown and short circuits [12]. In worst-case scenarios, the accumulation of heat can initiate a fire, posing a severe threat to both life and property. Understanding and mitigating these risks are essential for improving electrical system safety, as fires caused by cable failures can result in significant damage, loss of life, and disruptions to critical infrastructure. By elucidating the mechanisms underlying fire initiation in Cu insulated PVC cables under overcurrent conditions, this research aims to inform the development of preventive measures and safety protocols to minimize the likelihood of catastrophic failures and enhance the resilience of electrical systems.

Despite the extensive use of Cu insulated PVC cables in electrical systems, there remains a notable gap in understanding the specific effects of overcurrent on these cables and their resistance to fire initiation [13]. While existing literature acknowledges the risks associated with overcurrent conditions and the potential for thermal degradation of PVC insulation, comprehensive studies investigating the intricate relationship between overcurrent effects, thermal behavior, and fire resistance of Cu insulated PVC cables are limited. Moreover, the mechanisms governing fire initiation in these cables under overcurrent conditions are not fully understood, hampering efforts to develop effective preventive measures and safety protocols. Consequently, there is a pressing need for further investigation to fill these gaps and advance understanding in the field. By conducting systematic experiments and analysis, this research seeks to bridge the existing knowledge gap and provide valuable insights into the factors influencing the fire resistance of Cu insulated PVC cables under overcurrent conditions, ultimately contributing to the development of more robust safety standards and cable designs in electrical engineering applications.

By investigating the effects of overcurrent on Cu insulated PVC cables and evaluating their fire resistance, this study addresses a critical gap in existing knowledge and contributes valuable insights into the behavior of electrical cables under adverse conditions. The novel combination of thermal imaging, macrostructure analysis, and absorbed energy testing allows for a comprehensive examination of the thermal response and fire resistance of Cu insulated PVC cables, offering new perspectives on cable performance and safety. The findings of this research are expected to inform the development of safer cable designs and enhance safety protocols in electrical systems by providing data-driven recommendations for mitigating the risks associated with overcurrent conditions and fire initiation. By correlating the thermal behavior of the cables with their structural integrity and fire resistance, the study aims to elucidate the underlying mechanisms governing fire initiation and propagation in Cu insulated PVC cables under overcurrent conditions. Ultimately, the research endeavors to provide valuable insights into the factors influencing the safety and reliability of electrical systems and contribute to the development of enhanced safety protocols and cable designs in the field of electrical engineering.

2. METHOD

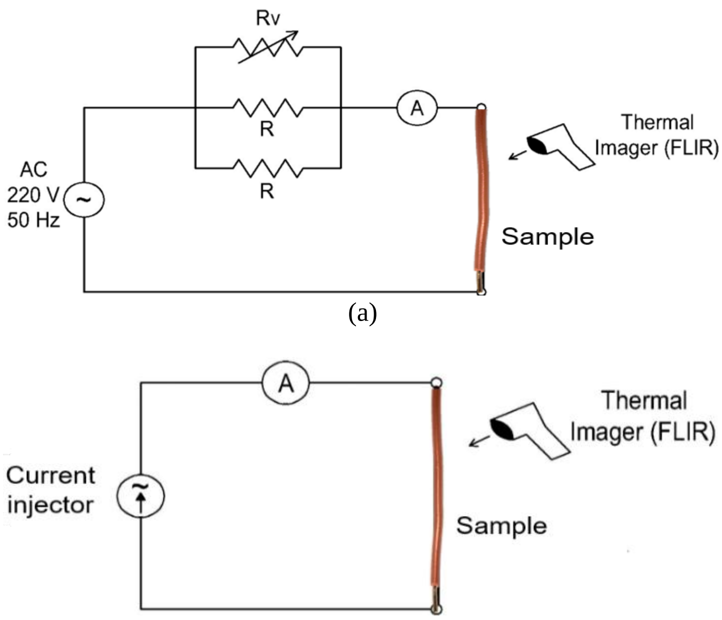
The samples utilized in this study comprise Cu insulated PVC cables measuring 1×1.5 mm (NYA), specifically identified as brand 046620.3 Eterna CU/PVC 1.5 mm² 450/7500 NYA. These cables were chosen to represent a commonly used type in electrical installations. The properties of pure Cu and PVC are detailed in Tables 1 and 2, respectively. Experimental procedures were carried out following an electrical circuit scheme illustrated in Figures 1(a) and (b). Six samples, denoted as CC0, CC21, CC50, CC70, CC100, and CC110, underwent exposure to varying levels of current as per predetermined conditions, as detailed in Table 3. Prior to each experimental treatment, dimensional measurements including weight and diameter were recorded for each sample. Additionally, room temperature measurements and cable temperature measurements (core and PVC insulation) were taken.

Table 1. The Cu properties

Item	Parameter
Density	8.96 g/cm
Electrical conductivity	5.9×107 Siemens/m
Thermal conductivity	386.00 W/(m·K) at 20 °C
Melting point	1083 °C
Boiling point	2595 °C

Table 2. The PVC properties

Item	Parameter
Density	1.38 g/cm
Volume resistivity	5.9×107 Siemens/m
Surface resistivity	386.00 W/(m·K) at 20 °C
Dielectric strength (breakdown)	14–20 Kv/mm
Melting point	212 °C



(a)

(b)

Figure 1. Electrical circuit experimental treatment depicting: (a) current values below the current carrying capacity and (b) current values above the current carrying capacity, representing overcurrent conditions

Table 3. The experiment treatment of samples

Samples	Electrical voltage (V)	Electrical current (A)	Time (min)
CCO	220	0	5
CC21		21	
CC50		50	
CC70		70	
CC100		100	
CC110		110	

Characterization of the samples involved thermal imaging and macrostructure analysis using Poics MC Photo Module. Additionally, joule heating was calculated using (1). Q is the total heat generated (joules), V is the applied voltage load (volts), I is the electric current (A) and t is time (seconds). These methods allowed for a comprehensive examination of the thermal behavior and structural integrity of the Cu wire insulated PVC cables under varying overcurrent conditions.

$$Q = V.I.t \tag{1}$$

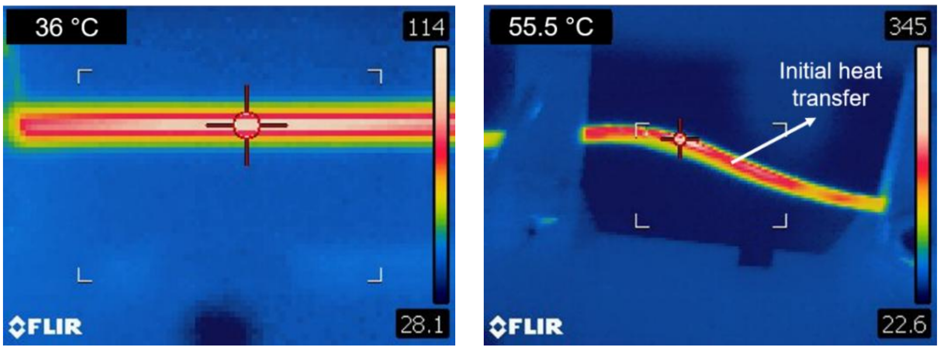
3. RESULTS AND DISCUSSION

3.1. Thermal imaging

The CC0 sample, which was not subjected to any electric current but only a voltage load of 220 V, exhibited a measured temperature of 36 °C, as shown in Figure 2(a). The thermal image displayed uniform temperature distribution across both the insulation and Cu surface, with no discernible color variation or hotspot detected. This uniform temperature profile indicates that the cable experienced minimal heating under the applied voltage load, consistent with the absence of current flow. The absence of hotspots suggests that no excessive heating or resistance-induced thermal anomalies occurred within the cable structure, reaffirming its intact insulation and undamaged conductor.

As the CC0 sample was not subjected to electric current, transient thermal responses associated with dynamic events such as power surges or transient overcurrent conditions were not applicable in this scenario. The stable and uniform temperature distribution observed in the thermal image indicates that the cable maintained a steady-state thermal equilibrium under the applied voltage load, without exhibiting any transient thermal fluctuations. Overall, the thermal imaging analysis of the CC0 sample demonstrates its stable thermal behavior and intact insulation integrity under the applied voltage load. The absence of hotspots, temperature gradients, or transient thermal responses indicates that the cable remained thermally stable and exhibited no signs of degradation or abnormal thermal behavior in the absence of electric current flow.

Figure 2(b) depicts the condition of the CC21 sample after 5 minutes of exposure to a 21 A current under a constant voltage load of 220 V, resulting in a measured temperature of 55.5 °C. The thermal image of the CC21 sample exhibits localized areas of elevated temperature, indicative of hotspots along the length of the cable. These hotspots likely correspond to regions of increased resistance or localized heating within the cable structure, resulting from the flow of electric current [14]. The presence of hotspots suggests that the cable experienced thermal stress and localized overheating, potentially leading to insulation degradation or conductor damage [15].



(a) (b)

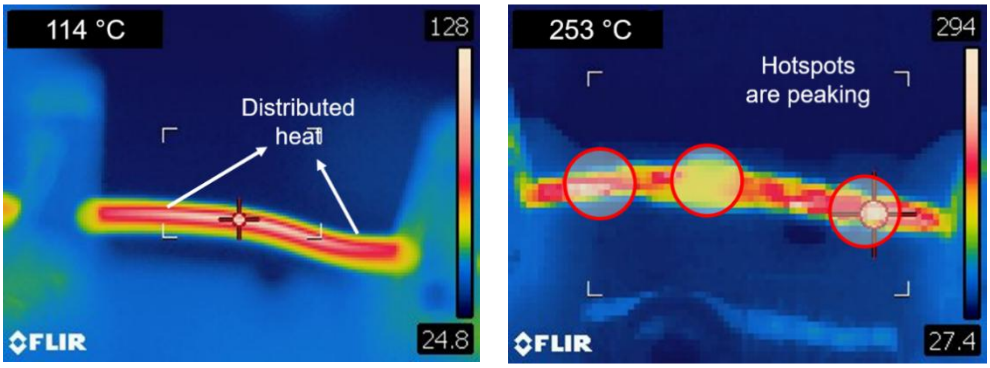
Figure 2. Image from real-time thermal infra-red camera on: (a) CCO and (b) CC21 samples

In contrast to the uniform temperature distribution observed in the CC0 sample, the thermal image of the CC21 sample displays uneven temperature gradients across the cable surface. Variations in temperature gradients indicate uneven heat dissipation [16] and thermal conductivity [17] within the cable structure, reflecting the non-uniform distribution of electric current and thermal energy. The presence of temperature gradients highlights the dynamic thermal response of the cable to the applied current load, with localized areas experiencing higher temperatures than others due to differences in resistance and heat dissipation [18]. The observed temperature changes in the CC21 sample reflect a transient thermal response to the applied current load, with initial heat transfer occurring despite the uneven temperature distribution. The non-uniform temperature profile suggests that thermal equilibrium has not yet been achieved within the cable structure, indicating ongoing thermal dynamics and heat dissipation processes [19].

Figure 3(a) presents an image captured from a real-time thermal infrared camera depicting the CC50 sample, which was subjected to a current of 50 A for a duration of 5 minutes. The thermal image reveals a relatively uniform distribution of heat across the entire surface of the cable, indicating effective heat dissipation and minimal localized temperature variations. The thermal image of the CC50 sample does not exhibit any discernible hotspots or areas of localized temperature elevation. The absence of hotspots suggests that the cable maintained stable thermal conditions and experienced uniform heat distribution under the applied current load. This indicates that the cable was able to dissipate heat effectively without encountering significant resistance-induced thermal anomalies or localized overheating.

Consistent with the absence of hotspots, the thermal image of the CC50 sample displays uniform temperature gradients along the length of the cable. The lack of temperature variations across the cable surface suggests uniform heat dissipation and thermal conductivity within the cable structure [20]. This indicates that the cable maintained a consistent thermal profile, with no significant differences in temperature between different sections or regions of the cable. The observed uniform distribution of heat in the CC50 sample suggests a stable transient thermal response to the applied current load. The absence of transient thermal fluctuations or non-uniform temperature profiles indicates that the cable reached a steady-state thermal equilibrium relatively quickly and maintained stable thermal conditions throughout the duration of the experiment [21]. This implies that the cable exhibited predictable and consistent thermal behavior under the applied current load, with minimal transient effects or thermal dynamics.

In Figure 3(b), an image captured from a real-time thermal infrared camera displays the CC70 sample, exposed to a current of 70 A. The thermal image reveals the emergence of several hotspots and an overall rise in temperature across the cable’s surface. The appearance of hotspots in the CC70 sample indicates localized areas experiencing elevated temperatures. Hotspots typically arise due to heightened resistance or localized heating within the cable’s structure, often triggered by factors such as suboptimal contact connections, insulation deterioration, or excessive current flow [22]. The emergence of hotspots contributes to non-uniform temperature gradients across the cable’s surface. Temperature gradients result from variations in heat dissipation and thermal conductivity within the cable’s structure. With hotspots present, certain areas experience higher temperatures than adjacent regions, leading to uneven temperature distributions. This phenomenon stems from the uneven distribution of heat generated by current flow, compounded by differences in thermal properties and material composition throughout the cable’s length.

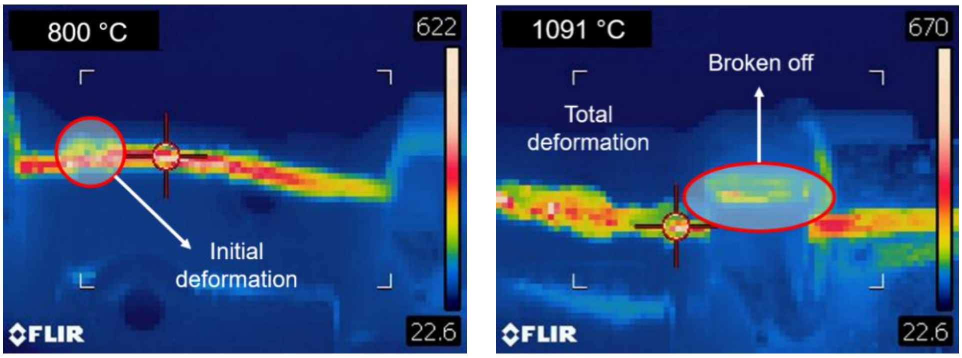


(a) (b)

Figure 3. Image from real-time thermal infra-red camera on: (a) CC50 and (b) CC70 samples

Figure 4 displays thermal images captured from a real-time infrared camera showcasing the CC100 on Figure 4(a) and CC110 on Figure 4(b). The CC100 sample reached a temperature of 800 °C, while the CC110 sample recorded a temperature of 1091 °C. The elevated temperatures observed in both the CC100 and CC110 samples suggest the presence of severe localized heating, likely stemming from significant resistance or thermal stress within the cable structure. Such high temperatures indicate substantial thermal anomalies, which may result from factors like excessive current flow, insulation breakdown, or poor contact connections.

The extreme temperatures seen in the CC100 and CC110 samples imply considerable temperature variations across their surfaces. These temperature gradients likely arise from uneven heat dissipation and thermal conductivity within the cable structure [23]. The intense heating and localized burning observed in both samples suggest an uneven distribution of heat, with some areas experiencing significantly higher temperatures than others. The deformation and burning witnessed in the CC100 and CC110 samples indicate a rapid and severe transient thermal response to the applied current load [24]. This rapid temperature increase and structural damage indicate swift thermal degradation and failure of the cables. Such transient thermal responses emphasize the urgency of monitoring and mitigating thermal effects to prevent catastrophic failures and ensure electrical system safety and reliability.



(a) (b)

Figure 4. Image from real-time thermal infra-red camera on: (a) CC100 and (b) CC110 samples

3.2. Macrostructure analysis

The macrostructural analysis of the cable samples after overcurrent testing provides valuable insights into the physical changes and damage incurred by the cables under extreme operating conditions. In this study, the Poics MC Photo Module tool was utilized to capture detailed macrostructural images of each sample, allowing for a comprehensive examination of their physical characteristics and structural integrity. This tool offers high-resolution imaging capabilities, enabling the visualization of any visible changes or damage that may have occurred to the cable samples during testing. By analyzing the macrostructural images alongside the accompanying data on sample mass, diameter, final temperature, and physical characteristics as shown in Table 4.

Table 4. Final properties of cable samples that have been treated

Samples	Mass (gr)	Diameter (mm)	Final temperature (°C)	Physical characteristics
CC0	5.5	1.5	36	Nothing happens visually macro
CC21	5.2	1.36	55.5	Nothing happens visually macro
CC50	5.1	1.35	114	Emits light smoke
CC70	5.0	1.31	253	The insulation melted at several points
CC100	4.5	1.30	800	Massive deformation and decomposition
CC110	4.4	1.29	1091	The insulation layer is completely lost

Figure 5 shows a high resolution visual image of each sample after overcurrent treatment. The CC0 sample, which was not subjected to any electric current, exhibited no visible macrostructural changes. This result aligns with the minimal thermal effects observed in the thermal imaging analysis, where the sample maintained a stable temperature of 36 °C. The absence of macrostructural changes indicates that the cable structure remained intact and undamaged under the applied voltage load. Similar to the CC0 sample, the CC21 sample did not display any visible macrostructural changes. Despite experiencing a slightly elevated temperature of 55.5 °C, the cable structure remained unaffected. This suggests that the sample was able to withstand the applied current load without undergoing significant physical alterations. The CC50 sample exhibited slight physical changes, emitting light smoke during the overcurrent testing. This phenomenon indicates the onset of thermal decomposition or pyrolysis within the cable structure [25], [26], likely due to the elevated temperature reached during testing. Despite emitting smoke, the cable maintained its structural integrity without visible signs of deformation or damage.

The CC70 sample experienced more significant physical changes, with the insulation melting at several points along the cable length [27]. This melting of the insulation suggests the occurrence of thermal degradation or pyrolysis, leading to the softening and deformation of the insulation material [28]. These changes indicate the cable's reduced structural integrity and potential vulnerability to damage under prolonged overcurrent conditions. The CC100 sample underwent extensive physical changes, including massive deformation and decomposition of the cable structure. The high final temperature of 800 °C likely caused the insulation and other cable components to degrade rapidly, resulting in visible deformations and decomposition. These drastic physical alterations indicate severe damage to the cable, rendering it unsuitable for further use.

The CC110 sample experienced catastrophic damage, with the insulation layer completely lost and the cable structure severely compromised. The extremely high final temperature of 1,091 °C led to the complete destruction of the insulation material, exposing the underlying conductor and resulting in irreversible damage. This catastrophic failure underscores the critical importance of implementing effective safety measures to prevent overheating and overcurrent conditions in electrical systems.

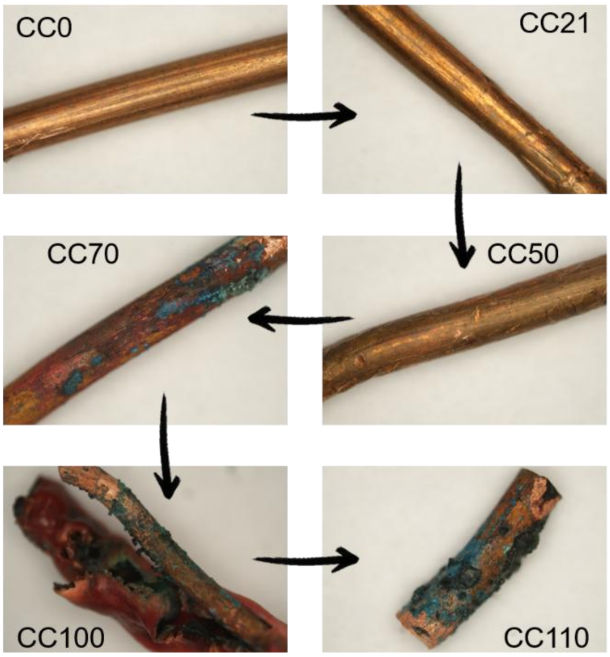


Figure 5. Visual changes in macrostructure taken with the Poics MC Photo Module from all samples

3.3. Joule heating

Joule heating, also known as resistive heating, occurs when electric current passes through a conductor and encounters resistance, resulting in the conversion of electrical energy into heat [29]. In this study, the Joule heating values were determined for each cable sample subjected to varying levels of current under a constant voltage of 220 volts for a duration of 300 seconds. Table 5 presents joule heating calculation data for each cable sample. The CC0 sample, which did not receive any electric current, recorded a Joule heating value of 0 J. This result aligns with expectations, as Joule heating occurs only when current flows through a conductor and encounters resistance. Since no current was applied to the CC0 sample, no Joule heating occurred, highlighting the absence of thermal energy generation within the cable.

Table 5. Joule heating of cable samples

Samples	Electrical voltage (V)	Electrical current (A)	Duration (s)	Joule heat (J)
CC0	220	0	300	0
CC21	220	21	300	1386000
CC50	220	50	300	3300000
CC70	220	70	300	4620000
CC100	220	100	300	6600000
CC110	220	110	300	7260000

The CC21 sample, subjected to a current of 21 A, exhibited a Joule heating value of 1,386,000 joules. This substantial heating is attributable to the flow of current through the cable's conductor, encountering resistance and generating thermal energy in the process [30], [31]. Despite the relatively small diameter of 1.5 mm, the Joule heating value indicates significant thermal energy generation within the cable due to the applied current [32]. With a current of 50 amperes, the CC50 sample experienced a Joule heating value of 3,300,000 joules. The increase in current flow led to a proportional increase in Joule heating, resulting in higher thermal energy generation within the cable [15], [17]. Despite the cable's small diameter, the substantial Joule heating value underscores the significant thermal stress experienced by the cable under overcurrent conditions [9], [33].

The CC70 sample, subjected to a current of 70 amperes, recorded a Joule heating value of 4,620,000 joules. The higher current flow resulted in a corresponding increase in Joule heating, leading to greater thermal energy generation within the cable [19]. The substantial Joule heating value highlights the heightened thermal stress experienced by the cable under more severe overcurrent conditions. With a current of 100 amperes, the CC100 sample exhibited a Joule heating value of 6,600,000 joules. The significant increase in current flow led to a substantial rise in Joule heating, indicating intense thermal energy generation within the cable. Despite the cable’s small diameter, the high Joule heating value reflects the severe thermal stress experienced by the cable under extreme overcurrent conditions. The CC110 sample, subjected to the highest current level of 110 amperes, recorded the highest Joule heating value of 7,260,000 joules. The extremely high current flow resulted in a proportional increase in Joule heating, leading to intense thermal energy generation within the cable [34]. The substantial Joule heating value underscores the critical importance of managing overcurrent conditions to prevent excessive thermal stress and ensure the reliability and safety of electrical systems [31], [35].

Figure 6 illustrates the relationship between the electric current applied to the cable samples and the corresponding heat energy generated, quantified in joules. As the current flowing through the cable increases, the amount of heat energy generated also increases, resulting in a proportional relationship between current and Joule heating [36]. The phenomenon depicted in Figure 6 is governed by Joule’s Law, which states that the heat generated in a conductor is directly proportional to the square of the electric current passing through it and the resistance of the conductor. In the context of the cable samples tested, the increase in electric current leads to a corresponding increase in the rate of energy dissipation in the form of heat. This phenomenon occurs due to the resistance encountered by the electric current as it flows through the cable conductor, resulting in the conversion of electrical energy into thermal energy.

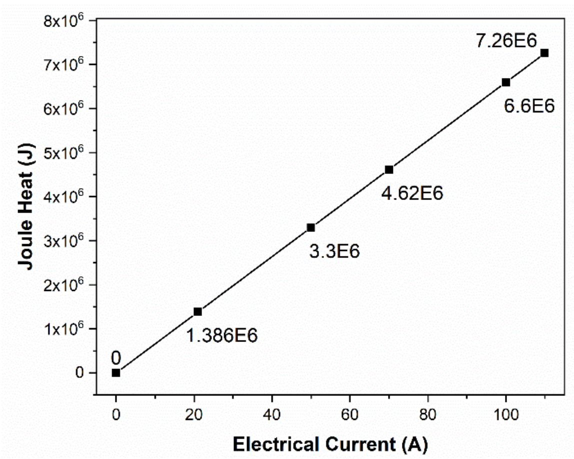


Figure 6. The relationship between the amount of current received by the cable samples and the heat energy produced

The observed relationship between current and Joule heating can be explained by Ohm’s Law, which describes the relationship between voltage (V), current (I), and resistance (R) in an electrical circuit. According to Ohm’s Law, the current flowing through a conductor is directly proportional to the voltage applied across it and inversely proportional to the resistance of the conductor [37]. Therefore, as the applied voltage remains constant, an increase in current results in a higher rate of energy dissipation [12], [33], [36] and, consequently, greater Joule heating within the cable samples. The phenomenon depicted in Figure 6 underscores the critical importance of managing electric current levels within electrical systems to prevent excessive heat generation [22] and mitigate the risk of thermal damage to cables and associated components. Additionally, it can inform the development of predictive models and simulation tools for assessing the thermal performance of cables under varying operating conditions, facilitating the design of more robust and resilient electrical systems.

Figure 7 depicts the relationship between the electrical current applied to the cable samples and the resulting temperature, as well as the final physical characteristics of the samples after testing. This graph provides insights into how variations in current levels affect the temperature profile of the cables and, subsequently, influence their physical properties. The data presented in Figure 7 reveal a clear correlation between current, temperature, and the final physical state of the cable samples, highlighting the complex interplay between electrical, thermal, and mechanical factors [21], [38]. The observed increase in temperature with higher current levels can be attributed to Joule heating, whereby the electrical energy dissipated in the form of heat within the cable conductor [18], [20], [21]. As the current passing through the cable increases, so does the rate of energy dissipation, resulting in a corresponding rise in temperature. This phenomenon follows Ohm's Law, which describes the relationship between current, voltage, and resistance in an electrical circuit. The increase in temperature due to Joule heating can lead to thermal stress and degradation of the cable materials, ultimately affecting their physical integrity and performance.

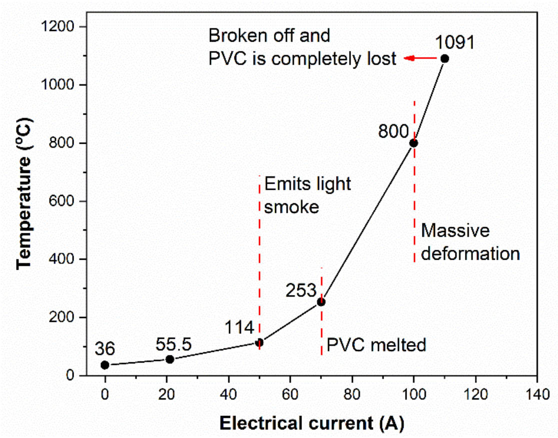


Figure 7. The electrical current vs temperature and final physical characteristics of the cable sample

The final physical characteristics of the cable samples, as observed after testing, are directly influenced by the temperature reached during operation. Higher temperatures can induce changes in the material properties of the cables, such as softening, melting, or degradation of the insulation and conductor materials. The data in Figure 7 indicate that as the temperature increases, the severity of physical damage to the cable samples also escalates. This relationship underscores the critical importance of managing temperature levels within electrical systems to prevent thermal damage and ensure the reliability and safety of cable installations. The relationship between temperature and the physical state of materials has been extensively studied in the field of materials science and engineering. These studies have shown that elevated temperatures can lead to various material transformations, including phase transitions, microstructural changes, and mechanical property degradation. For example, polymers commonly used in cable insulation can undergo thermal degradation, resulting in the loss of mechanical strength and flexibility. Similarly, metals such as Cu, used in cable conductors, can experience softening and deformation at high temperatures, leading to reduced electrical conductivity and mechanical integrity.

4. CONCLUSION

This study demonstrated a clear correlation between increased current and higher temperatures, with Joule heating values rising from 0 J in the CC0 sample to 7,260,000 J in the CC110 sample. Physical observations showed progressive damage, including minor deformations at 253 °C and complete insulation loss at 1091 °C. The research highlights the importance of managing current levels to prevent excessive thermal stress and ensure cable reliability. By understanding the interplay between electrical, thermal, and mechanical factors, this study informs strategies for optimizing cable. Future work could explore the effects of varying insulation materials and geometries on thermal performance, as well as the development of advanced monitoring systems for real-time assessment of cable conditions. Additionally, investigating long-term performance and degradation mechanisms under continuous overcurrent conditions could further enhance safety protocols and design standards in electrical systems.

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