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Utilization of Capacitor Bank for Electromagnetic Pulse Crimping

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Abstract

Capacitors play an important role in an electrical system. They have numerous applications in the field of lasers, fast X-ray, neutron sources, electromagnetic pulse generators, electron beam accelerators, plasma generation and electromagnetic welding of materials. One of the applications of high voltage capacitors as energy storage and discharge devices is in the crimping of cables using the electromagnetic pulse forming technique. This research paper investigates the use of a high-voltage energy storage capacitor with a capacitance of 208 microfarads and rated voltage of 44 kV to perform Electromagnetic Pulse Crimping (EMPC) of lugs for 70 mm^2 and 120 mm^2 cables. The capacitor operates at 12 kV and is discharged to produce a high current that generates a strong magnetic field of up to 20 Tesla, which is utilized for joining the cable conductor and the lug. The study examines the performance of the capacitor under different operating values such as voltage, capacitance, and discharge time and investigates the effect of these parameters on the termination quality. The paper presents the experimental results of the crimping, which include the contact resistance, weld strength, microstructure, and defects of the welded joints. The results indicate that the capacitor-based electromagnetic pulse crimping produces welds with high strength and minimal defects. Additionally, the paper discusses the future scope of research in this area and the potential applications of such capacitors in other welding techniques. The findings of this research paper provide valuable insights for engineers and researchers working in the field of energy storage, high-voltage applications and welding.

Keywords: Electromagnetic Pulse Crimping, High Voltage-Energy Storage Capacitor Bank

1. Introduction

A high-quality termination of a cable is necessary for linking any equipment within an electrical system. Cables consist of multiple metal strands that are intertwined and bound together using lugs. The crimping process for cables serves the purpose of ensuring a secure electrical connection that exhibits minimal contact resistance and subsequently limits temperature increase. Traditionally, crimping involves removing the cable's end insulation, inserting it into a lug, and then employing mechanical force to compress it. This mechanical crimping procedure typically employs tools or hydraulic presses. The inherent flexibility of the metal within crimped connections renders them resistant to both vibrations and sudden temperature fluctuations. Leveraging magnetic pulse crimping on lugs would result in uniform pressure distribution across the lug, thereby enhancing contact resistance and decreasing the gap between the metal strands within the cable.

The Magnetic pulse crimping requires a high magnetic field of the order of 20 Tesla, which is generated by flowing a high current pulse in the coil. To achieve this high-energy pulse, a high-energy storage element capable of releasing a high-energy pulse is required, and thus the High Voltage-Energy Storage Capacitor (HV-ESC) fits the application.

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1.1 High Voltage-Energy Storage Capacitor

The HV-ESC can store and release substantial electrical energy at high voltage levels making them indispensable in applications where rapid power delivery and energy storage are essential.

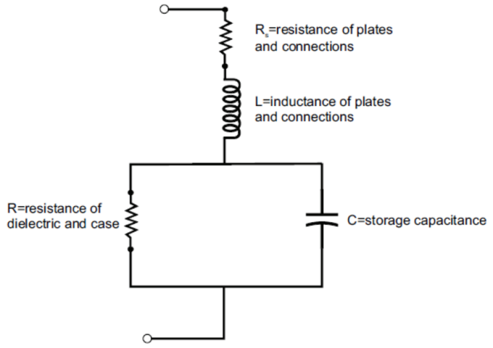

Figure 1. Electrical representation of HV-ESC.

The capacitor adheres to the standards of IEC 61071 and IS 13666. It employs bi-axially oriented, double-sided hazy Polypropylene films as the dielectric material and 99.9% pure Aluminum foil as the conductor. The capacitor's structure involves connecting multiple elements in a series-parallel arrangement, which varies based on the Voltage rating and energy requirements. This connection is established using contemporary soldering techniques. Figure 1 shows the lumped circuit model of the capacitor describing various resistances, inductance and storage capacitance. The Capacitor used has the following parameter values:

Capacitance: 208 microfarads
Rated Voltage: 44 kV
Dielectric: Polypropylene
Peak Current: 250 kA
Rated energy: 200 kJ

2. Theoretical Details

The Electromagnetic Pulse Crimping processes are governed by Maxwell's equations, electrodynamics equations and mechanical deformation equations. The schematic is shown in Figure 2. When the capacitor bank is charged to high voltage, it stores energy in the form of strong electric fields, then an ignitron switch is triggered and the capacitor bank discharges into the electromagnetic coil, it sets up a damped sinusoidal high current into the disk coil, which produces a high magnetic field inside the coil and the field shaper. The magnetic field produces the required circumferential pressure to compress the lug with cable. The lug then compresses with a high velocity towards the cable and the kinetic energy of the lug gets transformed into deformation energy. The energy transfer is given by the equation

Capacitor Energy = (Inductive energy + loss of energy during switching) = (Deformation Energy + electrical resistive loss + kinetic energy)

$$\frac{1}{2}\mathrm{CU}^2 = \frac{1}{2}\mathrm{LI}^2 + l = \mathrm{V}\sigma_{\mathrm{m}}\varepsilon + \mathrm{I}^2\mathrm{Rt} + \frac{1}{2}\mathrm{mv}^2$$

where,
U= Charging voltage on capacitor bank, Volts
V= Volume of job piece, m^3
m= mass of job piece, kg
v= velocity of job piece, m/s
C= charging capacitance, F
L= inductance of the circuit, H
R= resistance of the circuit, Ω
l= loss of energy during switching, J
σ_m= plastic stress, N/m^2
ε = plastic strain

Magnetic force is essential for crimping the lug, achieved by propelling the lug towards the cable strands with significant speed. This process ensures the creation of a reliable electrical connection between the cable strands and the lug. The achievement of uniform pressure around the lug's circumference is key for this purpose[1-3].

The formula to calculate the total pressure (P_{total}) necessary for lug compression is as follows:

$$P_{total} = P_{def} + P_{acc} \qquad [1]$$

where,
P_{acc} : required pressure for accelerating lug
P_{def} : required pressure for deforming the lug

The P_{def} is given by:

$$P_{def} = \frac{2.t.\sigma_y}{R} \qquad [2]$$

σ_y: Yield strength of the material.
t: thickness of the lug
R: Average lug radius

Acceleration of the lug with a density (ρ) to impact at a velocity (V_c) necessitates a certain pressure. This pressure required for accelerating the lug can be calculated using the formula:

$$P_{acc} = \frac{t.\rho.Vc^2}{2} \qquad [3]$$

So the required total is,

$$P_{total} = t.\left[\frac{\rho.Vc^2}{2} + \frac{2.\sigma y}{R}\right] \quad [4]$$

The generation of this pressure can be facilitated through a magnetic field produced by the discharge of a capacitor. This magnetic field's relation to the pressure can be expressed by the equation:

$$P = \frac{B^2}{2.\mu}\left(1 - e^{\frac{-2.t}{\delta}}\right) \quad [5]$$

B: Magnetic field required
δ: Skin depth

The current necessary for generating the magnetic field is represented by:

$$B = \frac{\mu.N.I}{l} \quad [6]$$

l: coil length
I: Peak current
N: Turns in coil

The charging voltage can be calculated by:

$$I = k.V.\sqrt{C/L} \quad [7]$$

k: Voltage reversal factor
V: Charging voltage

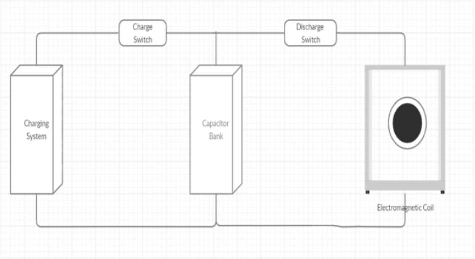

Figure 2. Schematic for electromagnetic pulse crimping process.

3. Experimental Details

The magnetic pulse crimping setup comprises a capacitor bank with a capacity of 208 μF, capable of being charged to 45 kV. The discharge of energy from this capacitor bank occurs through an ignitron switch into a three-turn disk coil equipped with a double slit field shaper, as illustrated in Figure 3. The field shaper possesses an internal diameter of 20 mm and a length of 15 mm. In the process, a copper lug, rolled with kepton tape, accommodates a 120 sq mm cable. This cable is then inserted within the field shaper. The copper lug itself has a thickness of 1.5 mm.

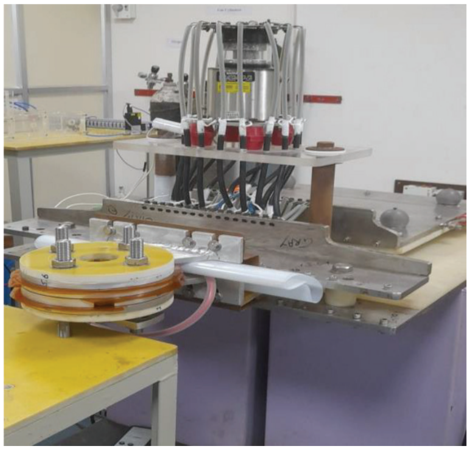

Figure 3. Experimental set-up for EMPC.

Once the lug-cable combination is positioned inside the field shaper using a press-fit mechanism, the capacitor bank is charged to a level of 12 kV. Subsequently, the ignitron switch is activated, causing the discharge of a current measuring 220 kA from the capacitor bank into the disk coil, as depicted in Figure 3. This process generates a magnetic field of 20 T within the confines of the field shaper. This magnetic field serves to create the necessary circumferential pressure, leading to the compression of the lug along with the cable.

4. Experimental Results

The 120 mm^2 lug is subjected to magnetic crimping, wherein it is compressed onto the cable using a discharge current of 220 kA into the coil. Conversely, a separate 120 mm^2 lug is mechanically crimped onto a similar cable. (Figure 4).

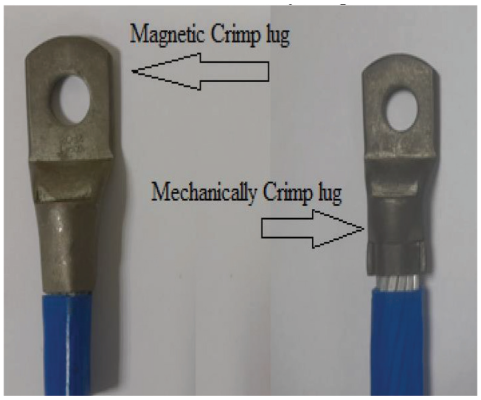

Figure 4. Comparison between mechanically crimped lug and magnetically crimped lug.

The contact resistance for the lug crimped through magnetic means measured 8.1 μΩ (Figure 5), whereas the lug that underwent mechanical crimping exhibited a contact resistance of 11.0 μΩ (Figure 6). To assess the leak rate from the strands enclosed within the lug and to examine the compression of strands or potential voids inside the lug, these lugs were dissected from the bottom.

Figure 5. Contact resistance measurement of magnetically crimped lug.

Using the magnetic pulse-crimped lug, a background vacuum of 10^{-1} mbar was attained within the leak detector. Additionally, a helium leak rate of 10^{-5} mbar.ltr/s was observed for the magnetically crimped lug.

Figure 6. Contact resistance measurement of mechanically crimped lug.

Due to a significant internal leak within the mechanically crimped lug, it was not feasible to achieve the necessary background vacuum for leak rate measurement. The background vacuum within the mechanically crimped lug could not be reduced below 20 mbar.

5. Conclusion

The magnetic pulse crimping technique stands as a technically advanced substitute for the mechanical crimping of lugs in electrical cable systems. This contactless method ensures a more evenly distributed pressure around the circumference without leaving tool marks, resulting in reduced contact resistance. Through magnetic pulse crimping, electrical cables and contacts experience a remarkably uniform and intensive compression, eliminating the presence of voids in the conductor strands. Additionally, this technique demands minimal setup time and boasts exceptional repeatability. It was established that the collision velocity of the lug with the cable should be around 100 m/s for successful and good-quality crimp. Tensile strength tests were performed on the samples crimped through the EPC technique and conventional methods. It was observed that the magnetically crimped cables were more than 21% stronger than those produced through the conventional method. Contact resistance measurement was done on samples. It was observed that the magnetically crimped cables showed more than 26% less electrical contact resistance as compared to the conventional method. By cutting the samples, a cross-section analysis of the samples was carried out. It was observed that the cable strands in crimps produced using the EPC technique had more contact area with the lug as compared to conventional crimping. A smooth profile and no sharp edges were observed on the samples using the magnetic pulse compression technology while such sharp edges were observed on the samples using the conventional method. These sharp edges often lead to corona discharge in high-voltage applications. This method also necessitates a brief setup period and delivers outstanding repeatability.

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