Reliable and fast connection of large-cross-section Milliken-type copper conductors by using cold spraying technology.

Christian **MICHELSEN**,Søren **ISAKSEN,** Yongming **XIA;** ReliBond, (Denmark), cm@relibond.com, yx@relibond.com, si@relibond.com

ABSTRACT

Conductors are increasing in size and complexity to meet future electricity demand. Large cross section Cu conductors for AC is often Milliken type with enamelled wires to mitigate issues related to skin effect. Connecting enamelled Milliken Cu-conductors using conventional connection principles normally requires a time-consuming, difficult, straining, and tedious conductor preparation procedure. This paper presents a novel connection principle utilizing cold spraying technology combined with a novel connection principle. Long term stability testing inspired by Cigre TB758 is performed. The results demonstrate a fast, reliable, and operator-independent connection solution for large cross section Cu conductors.

KEYWORDS

Connector, enamelled wires, Milliken conductor, AC systems.

INTRODUCTION

The growing global electricity demand is pushing cable manufacturers to develop new cable solution further increasing the current carrying capability. This tendency is resulting in increasing cable conductor cross sections both on DC and AC cable systems. Large cross section conductors above 1200mm^2 used in HV and EHV cables for AC systems will significantly be influenced by skin effect phenomena if not mitigated. Skin effect will increase the AC resistance of the conductor due to current density reduction towards the centre of the conductor. The changing magnetic field induces a strong opposing secondary current cancelling out the primary current towards the centre of the conductor. The skin effect in large cross section conductors can be reduced by utilizing Milliken conductor design (Fig. 1).

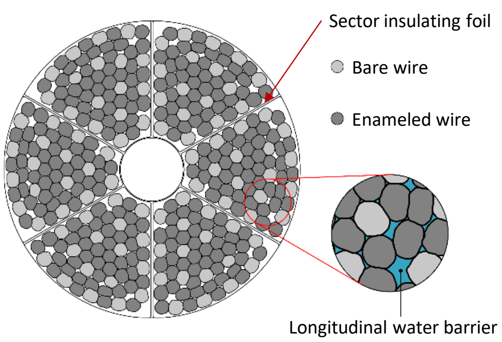

Fig. 1: Milliken conductor design with enamelled wires and longitudinal water barriers

The overall aim using the Milliken design is to divide the large cross section conductor into multiple smaller cross sections. An insulating foil can be introduced separating the large cross section conductor into several smaller sectors. Furthermore, insulation on the individual conductor wires can be introduced in the form of an oxide layer or an enamel/varnish, hence separating the large cross section conductor into several hundreds of smaller sectors. Longitudinal water barriers are often a part of the connector system to limit the damaging effect of accidental water intrusion into the conductor. Longitudinal water barriers are known to be in the form of swelling tapes, swelling powders as well as liquid water blocking compounds depending on conductor design and application.

Conductor connection and termination is an inevitable part of the cable system. The insulating foil, oxide, enamel and longitudinal water barriers are ensuring optimal cable conductor characteristics but all introducing significant complexity to the conductor connection process. These additional components will in this paper be referred to as Complex Conductor Components (CCC's).

Issues related to conventional connection principles

Conventional connection principles used today is commonly known to be welding, shear bolt connectors and hydraulic crimped connectors. CCC's needs to be removed prior the use of any of these conventional connection principles. Removal of CCC's is known to be time-consuming, difficult, straining, and potentially hazardous. Several removal methods exist such as special scraping tools, sandblasting, chemical removal, grinding etc. All removal methods require spreading out the conductor wires as depicted in fig. 2 to obtain sufficient access to the wire surface. Spreading out and recollecting conductor wires has a negative effect on the conductor structure as well as the conductor compactness and the procedure can potentially damage and/or break individual wires. Overall, this process can potentially reduce the current carrying capacity of the cable system if not carried out carefully, hence placing enhanced dependency on skills and cautiousness of the technician preparing the conductor.

Fig. 2: Spreading out conductor wires enabling prober cleaning of wires

CONNECTOR SYSTEM BASED ON COLD SPRAY TECHNOLOGY

This paper suggests a novel connection principle eliminating the necessity of removing any of the CCC's as well as the procedure of spreading out and recollecting the conductor wires. This results in a faster, safer, and more reliable connection technique compared to conventional system. Cold spray technology is used in combination with a novel connection principle removing known issues related to conventional connection principles.

Cold spray technology used on large cross section conductors

Cold Spray (CS) deposition technology is a fundamental part of the connection solution proposed in this paper. The main purpose using CS metal deposition technology is to convert all the individual and insulated wires constituting the Milliken conductor design (Fig. 1) to one electrically unified contact layer.

Fig. 3 is illustrating the main elements of the CS process. Solid metal powder particles are accelerated to above supersonic velocities. The particles are propelled by heated compressed gas and directed towards the conductor end surface. The CS process is partly facilitated by using a specially designed spray gun solution. The spray gun is scanning over the conductor surface with a controlled pattern, traverse speed and distance resulting in a CS contact layer gradually formed on the conductor end surface.

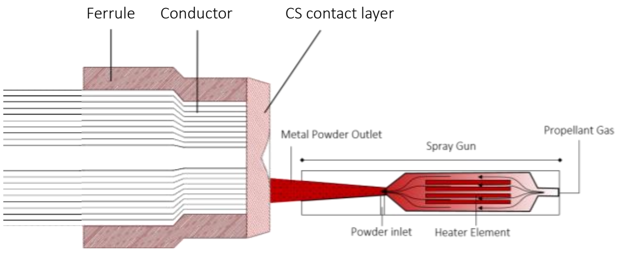

Fig. 3: Illustration of the CS process

The CS process is a low temperature metal deposition technology utilizing the particle kinetic energy to facilitate a bonding between the CS contact layer and the conductor wires. The thermal energy introduced to the conductor is proven not to affect the incorporated CCC's, hence the CCC's does not need to be removed prior the CS process. Fig. 4 is demonstrating such capability, where a CS contact layer have been applied on a Milliken conductor with enamelled wires. The enamel has not been removed prior the CS deposition process, and it is clearly seen that the CS contact layer have not affected the enamel or vice versa. Contrary to welding the low temperature of the CS process also eliminates the possibilities of damaging the cable insulation, hence external cooling of the conductor during the CS process is not required.

Due to the low temperature of the CS process conductor substrate and powder particles do not fuse together as known from e.g. welding. However, the process relies on a mechanical interlocking between particles and substrate to generate a strong adhesion. Particles must undergo significant deformation as well as penetrate the substrate surface during impact. To ensure sufficient deformation as well as substrate penetration particles must reach velocities above a critical value also referred to as critical velocities. The critical velocity is depending on the powder and substrate material properties. Particle velocity is highly depending on the pressure of the propellant gas, temperature increase in the spray gun, density of the propellant gas, particle temperature, size and shape. CS systems are generally divided in two pressure categories referred to as low- and high-pressure systems working with gas pressures from 5-10bar and 10-50bar, respectively. A significant difference in size and cost exists among these two systems. In this paper low pressure system with compressed air is utilized making it feasible to be used as an in-field solution during cable installation.

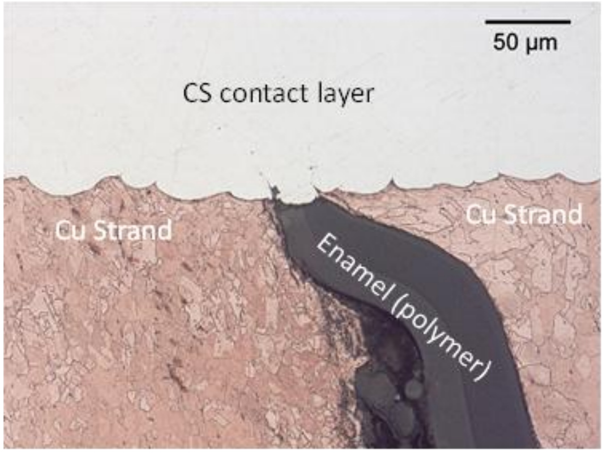

Fig. 4: Section view of a CS contact layer on a conductor with enamelled Cu wires.

CS is conventionally used on bulk materials. It is challenging to form one unified contact layer on the end of a conductor consisting of numerous individual conductor wires with CCC's as well as significant air gaps between said wires. A specially formulated Cu powder is developed to optimize the CS coating properties in regard to adhesion strength, surface uniformity, ductility, electric conductivity, thermal expansion, hardness and material compatibility. An example of a conductor with applied CS contact layer can be inspected in fig. 5 including a cross section of such layer. It is clearly seen that the surface of the CS contact layer is relatively rough, and this roughness must be accommodated by appropriate connector system.

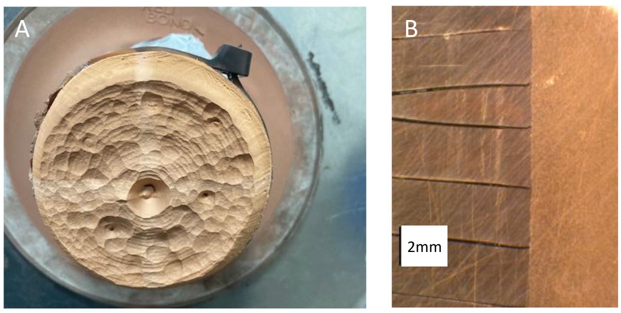

Fig. 5: Cu based CS contact layer applied on a 2500mm^2 Milliken Cu conductor with enamelled wires A) Frontal view B) Section view.

Novel 4-ring connector system

A novel 4-ring connector system is proposed to accommodate the characteristics introduced with CS contact layer.

An inner ferrule is mounted on both conductor ends to be connected. These inner ferrules are hereafter hydraulically crimped to ensure a mechanical fixation of conductor wires preventing relative movement of wires during external mechanical loads. A CS contact layer is then added to both conductor ends. The CS contact layer has a thickness of approximately 3mm and the duration of the CS process is approximately 20min for a 2500mm^2 Cu conductor. The two conductor ends with CS contact layer and crimped inner ferrule can now be connected using the 4-ring connector system (Fig.6). The main elements of the 4-ring connector system are the mechanical retaining ring, the axial clamping rods, the rear spring systems and the flexible centre contact element.

The mechanical retaining ring is fixed on the hydraulically crimped inner ferrule using a combination of stainless steel and brass based set screws. Axial clamping rods in combination with the mechanical retaining ring are enabling axial clamping force to be applied and maintained between both CS contact layers and the flexible centre contact element. The axial clamping rods are design to enable tightening using a standard open-ended wrench accessed from the side of the connector when installed on the conductor. The rear spring system enabling prober pre-tensioning of the axial clamping rods during installation without the use of special torque wrench. Hence the technician can visually detect when sufficient clamping forces has been applied to the system by inspecting the gradual gap reduction between the mechanical retaining ring and the rear spring system during the tightening process. The rear spring system also maintains constant clamping force on the flexible contact element and the CS contact layer.

The flexible contact element is consisting of a specially designed embossed Ag plate. The embossed structure ensures well distributed electrical contact points on both CS contact layers. Current is flowing in a direct path from conductor wires into the CS contact layers through the flexible centre contact element.

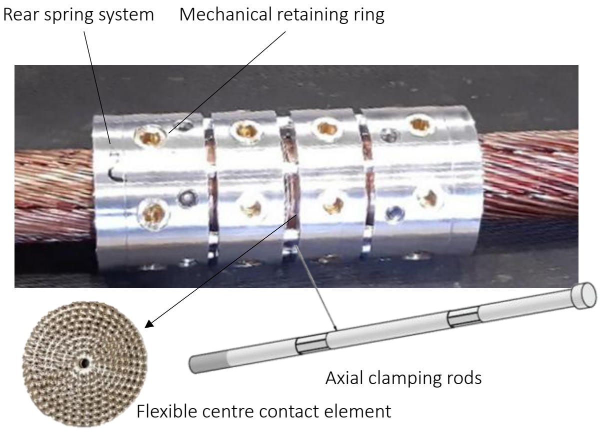

Fig. 6: The 4-ring connector system

EXPERIMENTAL VERIFICATION OF THE 4-RING CONNECTOR SYSTEM

A test program inspired by Cigre TB758 [1] has been developed to evaluate the performance of the 4-ring connector system. The test program consists of the following elements:

- Short circuit test: 6 short circuit shots at I_{rms}=100kA for 1 sec.
- Thermal stability: >200h with reference conductor temperature maintained at 120-126ºC
- Thermal cycling test: 200 heat cycles with reference conductor temperature maintained at 120-126ºC for approximately 4,5h.

The tests have been carried out at an external lab facility. Four test samples have been prepared consisting of 2X2500mm^2 enamelled Milliken Cu conductors connected with the 4-ring connection design. Total length of the four test samples was approximately 5m. Furthermore, a reference conductor was prepared from the same 2500mm^2 enamelled Cu conductor batch with an approximated length of 5m.

Short circuit test

Short circuit testing is performed on all four test samples simultaneously installed in a U shape configuration with 2 test samples on each side (Fig. 7). Approximately 5m distance between each side of the test loop is ensured using a solid connection bar. The distance is to limit the electromagnetic forces exerted on the test samples during the short circuit test.

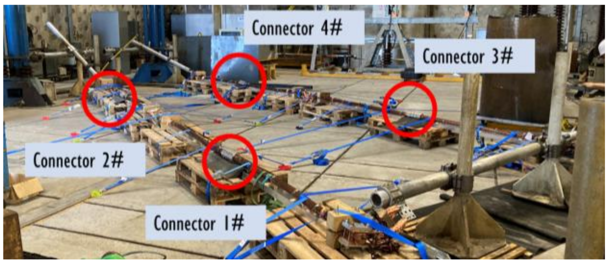

Fig. 7: Short circuit test loop

[1] specifies preheating of test samples to 90ºC prior short circuit shots and cooling of test sample to 90-95ºC between each shot. Preheating of the test samples was proven to be practically challenging and time duration between each shot was dictated by the limitation of the lab facility equipment rather than the temperature of the test samples, hence this part of the [1] was omitted.

Test values can be inspected in **Table** 1. An initial short circuit test shot was carried out followed by 6 successive short circuits at 100kA for 1 second. The 100kA short circuit test current was chosen to maximize the possible mechanical and thermal stress on the connector systems.

Table 1: Short circuit test values

Test No.	Time	I_{rms}	I_{peak}	Duration
[-]	[-]	[kA]	[kA]	[ms]
1	10:10	51.40	72.20	300
2	11:45	99.90	132.70	1000
3	12:06	99.90	151.80	1000
4	13:41	99.90	144.90	1000
5	14:02	100.00	153.70	1000
6	14:33	99.80	149.20	1000
7	15:03	99.80	156.90	1000

Connectors was inspected before and after the short circuit test and no visual change or damage could be detected.

Thermal stability

Test samples from the short circuit test was moved to a different location without dismantling the connectors. Fig. 8 is presenting the test loop configuration used during thermal stability as well as for the thermal cycling. The reference conductor temperature during the stability period was maintained by hysteresis regulation of the current. This means that current supply was turned ON and OFF during the stability period rather than regulating the current down to lower levels reaching equilibrium. Time duration for ON and OFF periods was on approximately 60s and 25s respectively. The average current level during ON period was registered to be 5654A. Inrush current when current is switched ON was measured to be between 20-30kA.The hysteresis regulation principle was chosen due to the limitation of the equipment available at the lab facility. It is uncertain whether the hysteresis current regulation principle could have an excessive deteriorating effect on the connector systems due to the inrush current level acting as more than 40.000 minor short circuits during the thermal stability and thermal cycling test.

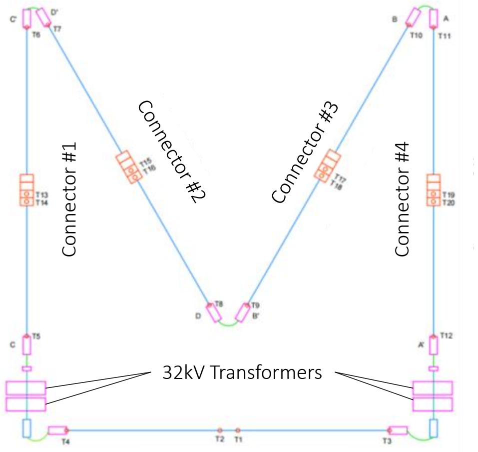

Fig. 8: Test loop used for thermal stability test and thermal cycling

Temperature of the 4 connectors as well as reference conductor is registered every 5 minutes during the entire thermal stability period. Fig. 9 is presenting temperature measurements for every 5 hours. Varying temperature differences between connector and reference conductor are registered during the stability period correlating with the change of ambient temperature.

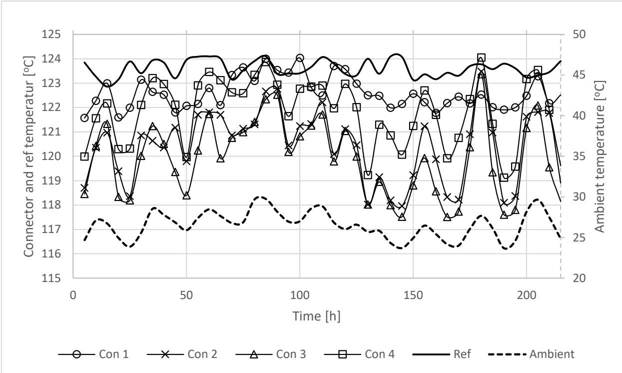

Fig. 9: Connector and reference temperature during 218h stability period registered every 5 hours

10 measurement campaigns have been carried out during the stability period (Table 2). Connector 1 is showing the highest temperature in 8 out of 10 measurement campaigns. However, connector temperature does not exceed reference temperature by more than 5K in any of the measurement campaigns. The measurement campaigns also demonstrates that connector temperatures arithmetic mean is below the maximum registered reference temperature, hence connectors are passing the test according to [1].

Table 2: Measurement campaign during thermal stability. Gray boxes showing the highest temperature for each measurement campaign

Stabilty duration	Temperature measurements [°C]					Minimum (Ref-Con) [K]
[h]	Ref	Con 1	Con 2	Con 3	Con 4	
8	122.6	123.2	120.8	121.7	121.7	-0.6
24	122.5	124.3	122.1	121.4	121.5	-1.8
48	122.7	122.1	121.3	119.6	122.5	0.2
72	122.7	123.4	121.2	121.4	122.2	-0.6
96	122.2	123.1	121.1	120.9	122.3	-0.9
120	122.4	123.0	120.5	120.0	122.0	-0.6
144	122.3	122.5	118.4	118.1	120.8	-0.2
168	122.1	122.7	120.3	119.9	122.3	-0.6
192	122.4	122.6	121.0	119.8	122.2	-0.2
214	122.7	122.6	119.5	119.2	120.5	0.0
Maximum Ref temp [°C]						122.7
Connector temperatures arithmetic mean [°C]						121.4

Thermal cycle test

Same loop configuration and current regulation principles as described for the thermal stability is used for the thermal cycle test. The reference conductor was maintained at a temperature level between 120-126°C for approximately 4,5hour on average in each of the 200 thermal cycles carried out, hence stability time is approximately 2,5h longer than required by [1]. A single thermal cycle can be inspected in fig. 10 showing acceptable performance by all 4 connectors.

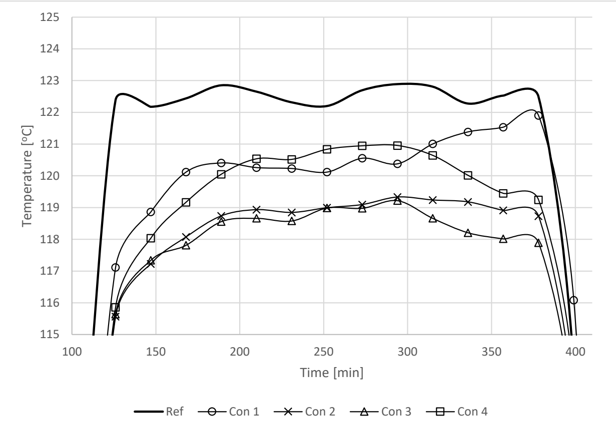

Fig. 10: Thermal cycle reference conductor and connector temperatures

21 measurement campaigns are made during the 200 thermal cycles (Table 3) showing the maximum temperature during the last 15min of the stability period. Maximum temperature for each measurement campaign is shifting between reference conductor, connector 1 and connector 4. Similar verification criteria according to [1] as described for the thermal stability test exist, hence connector temperature must not exceed reference temperature by more than 5K at any measurement campaign, and the connector temperatures arithmetic mean must be below maximum registered reference temperature. Both of these requirements are fulfilled, hence the connectors are successfully passing this test according to [1].

Table 3: Measurement campaign for thermal cycle test. Gray boxes show maximum temperature for each measurement campaign.

Cycle no	Max temperature measurements over 15min [°C]				
[-]	Ref	Con 1	Con 2	Con 3	Con 4
1	122.8	122.2	120.5	121.7	122.8
11	122.9	123.1	121.5	122.3	122.8
21	122.9	122.7	121.3	122.2	122.4
31	122.9	122.2	120.7	121.2	122.6
41	122.9	121.6	119.4	120.6	121.9
51	122.9	122.2	120.3	121.4	122.4
61	122.8	121.9	120.1	121.5	122.9
71	122.9	122.5	120.8	122.0	122.2
81	122.8	122.6	120.6	121.5	121.6
91	122.9	121.5	120.9	121.3	124.6
101	122.9	124.4	120.7	121.9	123.7
111	122.8	125.0	121.6	122.9	124.2
121	122.8	123.0	120.5	121.0	122.0
131	122.9	124.1	121.6	122.9	125.0
141	122.8	123.5	119.8	120.2	122.9
151	122.8	123.3	119.3	119.6	122.2
161	122.8	123.4	118.7	119.7	121.8
171	122.8	124.2	120.5	121.7	124.3
181	122.8	123.9	120.3	122.1	124.7
191	122.7	123.5	121.0	122.3	124.7
200	122.8	123.8	121.0	121.1	123.8
Maximum Ref temp [°C]					122.9
Connector temperatures arithmetic mean [°C]					122.0

Connector Improvement

The 4 connectors have successfully passed the tests based on [1]. However, the tests also show connector temperature relatively close to the temperature to the reference conductor. Possible improvements to the flexible centre contact element have been investigated. It is demonstrated that significant temperature reduction can be obtained just by replacing the flexible centre contact element to an optimized version V2 (Fig. 11). The V2 connector system is demonstrating a temperature reduction between 6,5-7,5K compared to original V1 design. Such improvement would introduce greater safety margins to the final connector system. Complete test of the optimized flexible centre contact element has yet not been carried out.

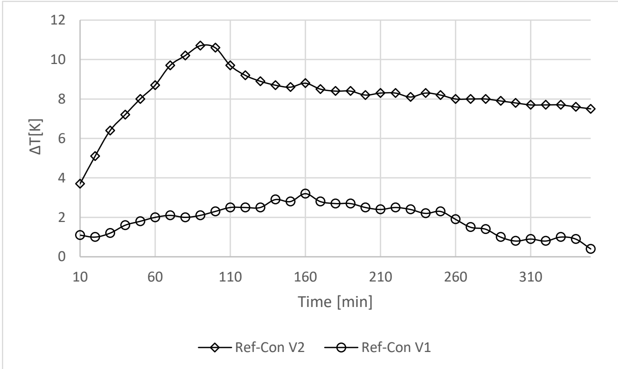

Fig. 11: Temperature difference between reference conductor and connector with first (V1) and second (V2) version of the flexible centre contact element

CONCLUSION

This paper has presented a new solution to connect large cross section Cu conductors utilizing cold spray metal deposition technology in combination with a novel 4-ring connector system. Short circuit test, thermal stability test and thermal cycling has been performed on 4 connectors installed on a 2500mm^2 enamelled Cu Milliken conductor. The connectors have successfully passed the verification criteria for each test ad defined in [1]. Further improvement to the connector system have been demonstrated enhancing the thermal performance of the connector system.

REFERENCES

[1] Cigre B1 Insulated Cables, 2019, Test regimes for HV and EHV cable connectors, Technical Brochure 758

GLOSSARY

AC: Alternating Current
Al: Aluminium
CCC: Complex Conductor Components
CS: Cold Spray
Cu: Copper
DC: Direct current
EHV: Extra High Voltage
HV: High Voltage