Reliable connector solutions for large cross-section aluminum conductors

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ABSTRACT

Copper is becoming a costly and scares resource. Hence, there is a tendency to replace copper with aluminum as conductor material in (E)HV underground and submarine cables. Because aluminum is susceptible to surface oxidation connector solutions must be carefully designed to ensure long-term stability, in particular for large cross-section aluminum conductors composed of many individual wires. Welding is by many today considered to be the only reliable connection method for such conductors. In this paper a new approach for connecting large cross-section aluminum conductors is presented. The method has the prospects of being reliable, safe, and fast.

KEYWORDS

Connectors, Al conductors, HV cables, EHV cables, welding, cold spraying

INTRODUCTION

The future society is based on electricity as the primary source of energy. Key sources of this energy supply, like offshore wind turbines, huge solar cell parks etc. will often be located far away from centre of usage. Hence, there is a strong growth in the need for new, high-capacity interconnection lines as well as local transmission lines. Nowadays, more and more of such new transmission lines on land are installed as underground cables and for cost reasons and because of scarcity of copper (Cu) many high-capacity cables are based on use of aluminum [Al] conductors.

To meet the ampacity requirements for such high-voltage cables the conductor cross-section must be large. Today cross-sections of 3,000 mm^2 or even bigger are becoming common [1]. Cross-sections of 4,500 mm^2 was presented at the Cigre 2022 Session, and even bigger conductor dimensions can be expected in the future.

Al is susceptible to fast oxidation, thus immediately creating an insulating layer on the wire surface. The electrically insulating oxide layer is beneficial to reduce skin effect phenomena, hence lowering AC resistance on large cross-section conductors. However, the oxidation phenomena create significant challenges when a reliable connector solution is to be designed. Main challenge is to ensure stable electrical contact to the innermost wires in the connector system.

Several different approaches already exist for connecting Al conductors [1].

Shear-bolt connectors are the most common solution due to their simplicity and ease of use. For their use in connecting larger Al conductors the main challenge is to ensure good, long-term connections to all the individual wires. Some companies are using a plurality of shear-bolts for larger Al conductors up to approx. 2,000 mm^2 in cross-section. This is combined with use of lubricants to reduce risks of having oxygen later penetrating to contact points. Otherwise, contact points can be vulnerable to oxygen exposure due to thermo-mechanical movements by the two interfacing bodies at load variations.

Crimped solutions are not so common for larger cross-section Al conductors due to lack of contact to innermost wires in the connector region [1].

A general concern for both shear-bolt and crimped solutions, when used for connecting larger cross-section Al conductors, is that they perform well when being newly installed, but the resistance to the innermost wires can gradually increase over time due to oxidation, in particular if the system has been exposed to short-circuits. Most installed systems are operated far below the maximum load level, which the systems are designed for. Likely, this is one of the reasons for why this failure mechanism has not been seen much in installed system but seen only as a tendency under long-term tests.

Welding is the most widely used solution for connecting large cross-section Al conductors and by some considered to be the only reliable method for connecting very large cross-section Al conductors [1]. By welding all individual wires at the conductor ends are physically made into one body. Hence, for connectors making use of welding there is no risk of reduced or lost contact between individual wires due to oxidation at vulnerable contact points.

However, use of welding for connecting large cross-section Al conductors also has its drawbacks. The welding process must be carried out very carefully and slowly to avoid that the heat from the welding process is damaging the nearby insulation of the cable. Forced cooling is necessary to protect the insulation from heat damage. Very skilled welders are required to carry out the welding process and there is lack of such specialist. Furthermore, the process creates un-healthy fumes and risks of fire. Some utilities [1] does not allow welding to be used at installation of their systems, and others are considering the same policy.

Hence, there is a need for developing an alternative method for connecting large cross-section Al conductors.

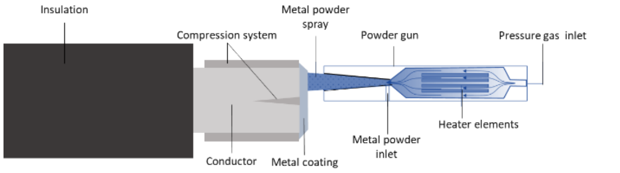
BASIC WORKING PRINCIPLE

A main benefit of the welding process is that it physically integrates all wires, hence avoid issues related to surface oxidation. In the solution proposed in this paper the same basic feature is accomplished by building a metallic coating on the end-facet of the two conductors to be connected. This coating is made by spraying very small metallic powder particles on the end facet of the conductor in a cold process, called cold spraying [CS]. Since this process can be carried out at low temperatures all the drawbacks of the welding process are avoided. The two coated end surfaces are connected by a so-called flex-element. All electrical contact points of the system are silver [Ag] coated. Hence, the connector solution has no vulnerable points for potential surface oxidation. Fig. 1 shows the basic principle of this connector solution.

COLD SPRAYING TECHNOLOGY

The connector approach is based on the use of cold CS as a key technology. CS is an additive manufacturing technique. The principle was invented, and first version developed by a group of scientists at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia [2], and first published in form of a patent application [3]. The technique is nowadays commonly used to repair worn or defect metallic parts either in production or on-site in the field.

Cold spraying process



Proposed connector principle

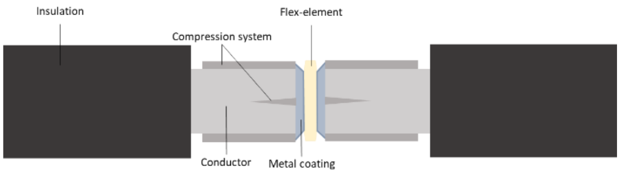


Fig. 1. Schematic diagrams

At CS very fine particles of metallic powder in the µm-range are sprayed through a nozzle on the relevant surface at very high velocities by use of a carrier gas heated to moderate temperature, see Fig. 1.

The particles impinging on the surface creates a kind of crater and adheres mechanically to the surface. The CS technique is flexible regarding the choice of metals to be deposited as well as the type of substrates to be coated. The CS exists in high-pressure versions, in the range 50 bars, as well as in low-pressure versions, typically operating around 7 bars. For very demanding requirements helium is optimal to be used as carrier gas. For more cost-efficient CS applications ambient air can be used.

Since the aim in this development has been to develop a process for connecting conductors in the field all results presented in this paper are based on the use of low-pressure CS equipment and using dry and oil-free ambient air as carrier gas.

In the laboratory experiments conducted in this work it has been found that the CS in combination with a 3D-like scanning technique under right process conditions is suitable for building a metallic coating on the contact-layer on the end-facets of cable conductors. Quality of the deposited contact layer; i.e., parameters like adhesion strength, conductivity, surface coverage etc., is very dependent on process parameters like powder composition, particles size and shape, gas temperature etc. Only limited thermal energy is introduced to the substrate, hence the coating process can be carried out without the need to remove organic or in-organic materials within the conductor area at the deposition zone. If coating powder and process parameters are optimized for the type of conductors to be coated, this contact-layer adheres well and has good electrical contact to all the individual wires of the conductor. Patent applications have been filed and granted for the concept of building such a contact-layer in a cold process as well as for relevant machinery for carrying out this process under controlled conditions [4, 5].

The developed process creates an electrically and mechanically bond between all the individual wires of a conductor. In contrast to welding, this process can be carried out without the need to clean the conductors beforehand for organic substances. Most of today's large cross-section Al conductors includes organic materials. Efficient AC-conductors of the Milliken type are including separation foils and all submarine cables and most underground cables today includes water penetration inhibitors. The CS process works well without any need of cleaning conductors for organic materials, including fluidic water blocking compounds.

Fig. 2 shows microscopic investigations of an experiment of a laser-welding of an enameled Cu-conductor with no pre-cleaning and for comparison a Cu contact-layer built on the end-facet of same type of conductor by CS process. CS leads to a more controllable and better connecting interface than welding.

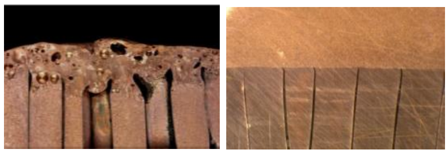


Fig. 2. Enameled coated Cu-wires being either laser-welded (left), or coated by CS (right)

For Al conductors we use Al as base coating material. To avoid oxidation of the deposited Al contact-layer a dual layer approach is used. First, a layer of Al, typically 2 - 3 mm in thickness, is built on the conductor end-facet. On top of this a thin layer of silver [Ag], a few hundred µm in thickness is sprayed. This Ag-layer will act as the contact surface. One of the benefits of the CS-process is that the impinging particles destroy any oxide-layer on the surface, so there is no risk of an oxide-layer in between the Al-wires and the Al base-coating, nor between this base-layer and the Ag top-layer. In fig. 3 such a dual layer contact-layer is shown.

Fig. 3. Al-base contact-layer with a top-layer of Ag on a 3,000 mm^2 Al Milliken-conductor

CONNECTOR SOLUTION. REQUIREMENTS

When designing and testing a connector solution it has to be proven that the connector repeatedly, at varying types of loads, always fulfils mechanical, electrical as well as thermal requirements. The final aim for the type of connector under development is that it will successfully pass the tests as defined in Cigre TB758 [1]. The tests are defined as follows, here adopted to a 3,000 mm^2 Al conductor:

a. Mechanical pre-stress test: 50kN
b. Short circuit test: 90°C pre heating and 6 times 45 kA for 5 sec (or corresponding heat-integral)

c. Constant high current stability test: Reference conductor at 120°C for 200h
d. Heat cycle stability test: Reference conductor at 120°C for 2h – Cooled to within 10K of ambient temperature - Repeat 200 times
e. Mechanical stress test: 50kN

Furthermore, the ambition for this development activity is to develop a connector solution, that dimensionally stays within specified limits defined as follows:

- total length: < 200 mm (from insulation to insulation when assembled)
- total diameter: < Conductor diameter + 30 mm, corresponding to voltage levels of 110 kV and above

In this paper design principles and preliminary experiments and results will be presented. The full test program to demonstrate compliance with TB 758, as listed above, has not yet been carried through.

DESIGN CONSIDERATIONS

A prober connector design shall fulfil the electrical, mechanical as well as thermal requirements.

Fixation of Al wires

In addition to the coating's beneficial features, it also adds an extra constraint to the connector design. To obtain good long-term electrical performance of the connector it is crucial that the coating deposited on the end facet of each individual wire maintains prober mechanical contact to the wire. This requires that relative movement between wires are prevented, hence prober interlocking of wires to withstand the mechanical stresses encountered during installation and varying loads throughout the expected lifetime of the connector.

Compression of an Al ferrule is a conventional solution for locking conductor wires to each other and to a surrounding body. For Al a quite long ferrule for compression is needed to ensure a good interlocking of the Al wires to the surrounding compressed ferrule. Because of this it can become difficult to meet the ambition to the length limitation of a connector design as specified.

To address this issue an alternative and new compression process, including a special compression tool and clamped components has been developed. The system is based on a bi-directional compression principle, combining an inside-out and an outside-in approach. This enables a locking of the wires to the surrounding body as well as a better interlocking of the inner-most wires. A cross-sectional view of the principle for this clamping system is shown in fig. 1.

Electrical contact principle

A key benefit of the CS coating process is that all individual wires of the conductor have a very low resistive way to the outer surface of the contact-layer. Typically, the conductivity of low-pressure CS-coating layer is about 50% of the conductivity of bulk material [6]. Furthermore, the risk of having an insulated surface layer of oxidized Al is eliminated by using the dual layer principle protecting the surface of the Al contact-layer with a thin CS deposited layer of Ag.

The basic principle of the solution being developed is to make use of a direct connection from one coating surface to the surface of the other contact-layer for obtaining a good electrical connection between the two conductors. To accomplish this a so-called low-resistance flex-element is inserted in-between the two opposed coated conductors, fig.1. To avoid issues related to oxidation all contact points of the flex-element are based on use of Ag-material. Two different types of connecting flex-elements have been tested in this work. Details and results are presented and discussed in following sections.

Mechanical strength of connector

In the work using conventional ferrule crimping technology the connector design, which is presented in a paper on connectors for enameled Cu-conductors [7], is applied. This is a 4-element type of connector system [Comp1] and is shown in fig. 4, top.

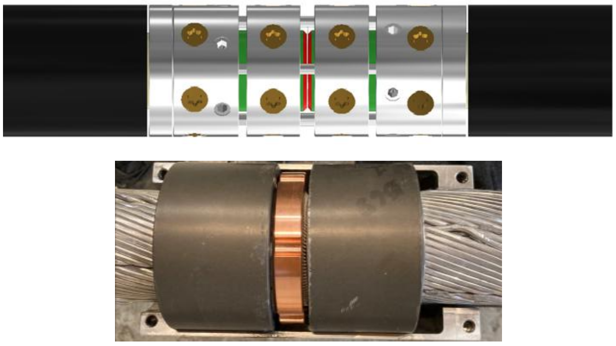


Fig. 4. 4-element connector system (Comp1, top), and bi-directional clamping solution (Comp2, bottom)

For the newly invented bi-directional compression system [Comp2] the principle for providing the mechanical strength of the connector is made by a cylindrical housing made of high strength Al-alloy surrounding the internal part of the connector system. This housing is via a spring-loaded axial tension system locked to the backside of the clamping system on both sides. Due to the principle and strength of the clamping system this solution can withstand increased tensile loads. The spring-loading provides longitudinal elasticity to ensure that system is back to initial position and at specified compressive force on the flex-element after relaxation.

EXPERIMENTS AND RESULTS

In this section experiments and results related to work on connector solutions for a 3,000 mm^2 5-sector Milliken Al conductor are presented. The two conductors to be connected have both been coated with an approximately 3 mm Al base contact-layer, and a 0.2 mm Ag top coating to avoid possible surface oxidation. The process for making such a double layer contact-layer on one conductor end takes approximately 20 minutes. Fig. 3 shows such a double-coated conductor end.

Experiments were made with the two different compression techniques described previously: Comp1, the conventional compressed ferrule technique, and Comp2, the bi-directional compression technique.

For each type of compression system experiments have been carried through with two different configurations of flex-elements connecting the contact-layers of the two conductors.

One type of flex-element consists of an embossed Ag-plate [Flex1], and the other of a Cu-based center element equipped with Ag-coated canted coil springs on both sides [Flex2], see fig. 5 for both.

Fig. 5. Flex-elements.
Embossed Ag-plate (Flex1, left), and
a canted coil spring flex-element (Flex2, right)

Flex1 has the benefit of providing low contact resistance between the two opposed contact-layers of the conductor ends. The limited axial flexibility of the embossed Ag-plate is compensated for by having built in longitudinal elasticity of the connector by spring-loads in the mechanical locking system. Flex2 has a higher contact resistance, but more axial flexibility preserving good electrical contact between the conductor ends also under tensile loads.

Finally, some extra experiments have been made to test the benefits and relevance of using the CS contact-layer as a common contact interface.

Electrical testing of the solutions is made in a high-current test loop. The loop can provide approx. 6,000 Amp. and enables a comparison of a 5m long connected system against a 5m long reference conductor of same type, see fig.6.

Fig.6 Thermal test loop (left), and
high current injection system (right)

A high current injection system, also making use of CS contact-layers and the embossed Ag-plate, has been developed to connect the test samples easily and quickly to the busbars of the test loop. This has the extra benefit of being a low-loss coupling, so no excess or disturbing heat is generated at the busbar injection point, see also fig. 6. In loop experiments high currents are used to heat the refence conductor to 120ºC and current is then reduced to the level necessary to keep temperature of reference conductor stable at this level. The temperature of the connector system is compared to reference conductor under these load condition.

Mechanical testing is done in a test bench capable of delivering a tensile load of up to 12 tons.

<u>Conventional compressed ferrule (Comp1)</u>

To avoid cracking soft Al ferrules are used. Consequently, 115 mm long crimp length and complex crimp procedures must be applied to obtain sufficient interlocking of the wires.

This resulted in a full connector length of approximately 250 mm. No sliding of conductor within compressed ferrule or movement of wires with respect to each other could be detected at 60 kN tensile load, i.e., better than the required 50 kN.

Embossed Ag-plate as flex-element (Flex1)

The results of the thermal tests of this connector system equipped with both embossed Ag-plate and canted coil spring flex-element (Flex2) are shown in Fig. 7 with reference conductor stabilized at 120ºC.

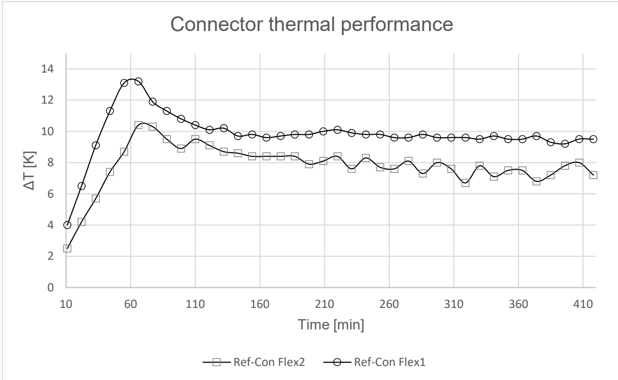


Fig. 7. Temperature difference between reference conductor and connector for Comp1 with embossed Ag-plate (Flex1), and canted coil (Flex2)

The temperature of the connector is 10ºK below the reference conductor.

30 thermal cycles have been carried through for the connector with Flex1, see fig. 8. Performance shows variations within ± 0.4ºK over these cycles, indicating good long-term stability of this system.

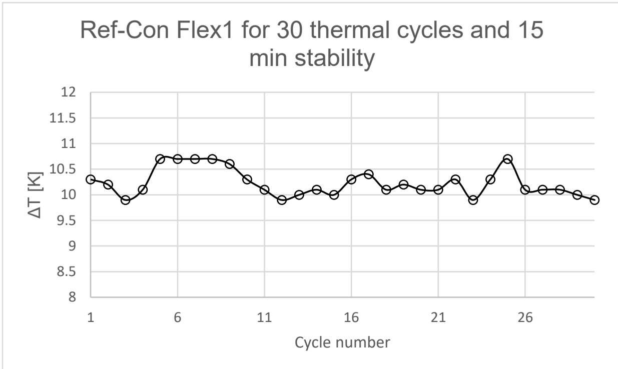


Fig. 8. Variation in stability of temperature difference between reference conductor and connector during 30 accelerated cycles

The results above indicate a low added resistance, if any, of the connecting system in form of the two contact-layers plus the embossed Ag-plate.

Canted coil spring system (Flex2)

The connector results of the thermal test of this connector system equipped with double sided ball-spring system is also shown in fig. 7.

For this connector system the temperature is consistently around 7.5ºK below the temperature of reference conductor.

The results show that the embossed Ag-plate flex-element results in a lower connector resistance than the canted coil spring. Both solutions fulfil the requirements at the thermal cycling.

To illustrate the benefits of having the contact-layer as a common contact surface for all individual wires an experiment was made assembling this Comp1 connector solution with the Flex2 center element but with no contact-layers on the conductor ends. The result of this experiment is shown in fig. 9.

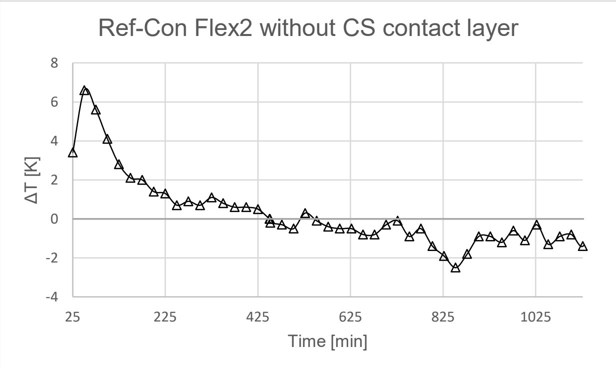


Fig.9. Stability tests showing temperature difference between reference conductor and a connector based on Comp1 compression and using a Flex2 element without any CS contact-layer on conductor end facets.

At start the connector temperature is below the temperature of the reference conductor, but slowly it increases, and after a few hours the temperature becomes higher than the temperature of the reference conductor and gradually increases.

Bi-directional compressed system (Comp2)

First versions of this new developed compressed system have been tested.

Mechanical tests have been conducted on enameled Cu conductors of 2,500 mm^2 cross-section. With a compressed length of 60 mm on both conductor ends no sliding of conductor within compressed ferrule or movement of wires with respect to each other could be detected at 90 kN tensile load. The total length for the housing used for the mechanical strength of the connector was below 200 mm with this compression solution, and a reduction of the total maximum length of 160 mm seems achievable.

Embossed Ag-plate as flex-element (Flex1)

The temperature performance of the embossed Ag-plate as flex-element is shown in fig. 10.

For this system the connector temperature after some time is consistently around 12ºK below the temperature of the reference conductor.

The conductor temperature at a distance of 250 mm from the connector was also measured. This temperature was approximately 5ºK below the temperature of the reference conductor, which should be expected having such a low connector temperature.

DC-resistance of the connector system has been measured to be approx. -0.6µΩ.

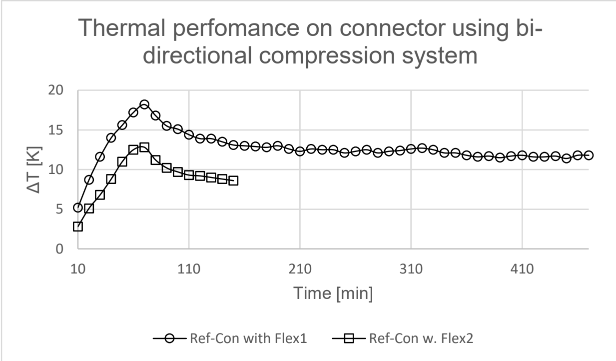


Fig. 10. Temperature difference between reference conductor and connector for Comp2 with embossed Ag-plate (Flex1), and canted coil (Flex2)

Canted coil spring system (Flex2)

The temperature performance of this connector system is also shown in fig. 10.

The temperature of the connector surface is in this case settles 8ºK below the temperature of the reference conductor, indicating a higher temperature of this connector system as compared to the embossed Ag-plate solution. This is also supported by the fact, that conductor temperature at a distance of 250 mm away from the connector in this case is close, approx. 1ºK below, to the reference conductor temperature.

DC-resistance of this connector system has been measured to be approx. 0.6µΩ, also consistent with a higher resistance for this system, than the system based on the embossed Ag-plate.

DISCUSSION

Only a part of the planned full test program for this new connector solution for large cross-section Al-conductors has been carried out until to now.

Experience from the work on Cu-based conductors has shown that quality of the compressed system in form of good inter-locking of conductor wires under tensile loads is essential for a connecting principle based on the building a contact-layer on the end of the conductor. The tensile tests for both type of compression technique have shown that this critical feature is achievable for both compression techniques tested in this work. Though, it still needs to be proven in a final testing, that this critical performance also prevails after long load periods, i.e., after 200 thermal cycle periods.

The electrical and related thermal behavior of both compression approaches are well within specified requirements. Because all relevant contact elements are Ag-coated, it is likely to believe that the connector solutions also will be able to pass 200 thermal cycles with success.

Relevant short circuit tests have not yet been conducted. It is well-known that Al conductors in general are more vulnerable to short circuit tests than Cu conductors. In another work [7] it has been shown, that the type of connector approaches presented here have no issues in passing relevant short circuit tests for Cu conductors. In the work presented here all current is passing through solid matter all the way from the wires until it reaches the Ag-surface of the contact-layers. Based on this fact, there is a good reason to believe, that the presented connector approaches will also be able to pass relevant short circuit tests.

Regarding dimensional performance the newly developed bi-directional compression system holds the promises to fulfill the strict requirements for a large Al-connector of not being longer than 200 mm in total.

Besides the use of the CS technique a key element in this connector approach is the use of a flex-element for direct connection between the two opposed contact-layers at the conductor ends. Only two different, and quite simple approaches, for such flex-elements are presented in this paper. Other possible solutions for providing similar or maybe even better flexibility and contact performance are known and used in the connector industry and will also be investigated and tested in the future.

CONCLUSION

A new approach for designing and making connector systems for large cross-section Al conductors has been presented.

The proposed solution is based on use of cold spraying technique to build a contact-layer on the end facet of such Al conductors. This contact-layer acts as a common low-loss contact point for all wires. Using this contacting technique, it is possible to build a connector solution that does not rely on any direct electrical contact points at Al surfaces. This significantly reduces the risks of failure mechanisms caused by surface oxidation of Al.

Furthermore, a new compression system enabling a shorter compression area has been developed and tested.

The proposed connector system has been proven to have good and promising electrical, mechanical, and thermal properties. Long-term thermal tests under varying loads, test of mechanical performance after long-term loads, and short circuit tests are needed to be carried out to demonstrate full performance according to [1].

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