Generator Rewind Technology and Efficiency Improvements
Implemented on Rewinds in Africa

By

Bill Moore, National Electric Coil
Dave Tarrant, Sebenzana Corporation
Rob Melaia, Marthinusen and Coutts

Abstract

This paper will focus on specific technology and efficiency improvements used during several generator rewinds done in South Africa and the DRC. One improvement includes transposition changes at two Kelvin, South Africa, generators, resulting in lower overall losses in the stator winding, and improved cycle time efficiency. Another improvement includes the incorporation of side ripple springs. Design discussions on the pro’s and con’s of multi-turn coils and bars are discussed, as well as VPI versus Resin-Rich manufacturing technology. Finally, case history discussions on recent rewinds and repairs in Africa are given.

Background

- Kelvin Rewinds Units 9 and 10 – GEC 75,000 kVA, H2 cooled, 11.8 kV, 50 Hz, Neccobond-E Roebel bars.
- Port Rex Spare Winding Supply to Eskom – East London, South Africa, Brush 70,000 kVA, 13.2 kV, 50 Hz, Neccobond-E Roebel Bars
- DRC – Democratic Republic of Congo Rewinds – Stator Windings Manufactured by NEC and installed by NEC Partner Marthinusen and Coutts:
  - Kolwezi Converter Station Plant, GE 70,000 kVA Synchronous Condensers, 750 rpm, 11.85 kV, 50 Hz, Neccobond-E Roebel Bar, 114 slots (2 units)
  - N’zilo Hydrogenerator Station, ACEC 30,000 kVA, 333.33 rpm, 6.6 kV, 50 Hz, Neccopress III, Multiturn Coil, 270 slots.

Photos of the rewinds at N’zilo and the one rewind at Kolwezi are shown below in Figures 1, 2 and 3.
Fig. 1 Kolwezi 70 MVA Synchronous Condenser Stator Rewind – Single Turn Bars

Fig. 2 and 3 N’zilo 30 MVA Hydrogenerator Stator Multturn Coil Winding Installation and Turn to Turn Testing
Conventional Coil Stator Rewind Improvement Areas

Generator stator rewinds, even on smaller machines with conventional cooling, hold the promise of significant improvements that can be made in several areas. Not only can there be a significant reliability increase offering longer life, significant reduction in losses is possible, in turn offering lower operating temperatures or uprating. Key areas of coil design improvements lie in the strand size and arrangement, ground wall dielectric strength, type and thickness, the transposition design, and the corona suppression system design. Each of these areas is discussed below.

Transposition

The right transposition is a critical choice in the preparation of a rewind, but most often this choice is made by the supplier rather than the owner. Bar/Coil transpositions are necessary to reduce and even eliminate circulating current losses in the coil. These losses are generated from the voltage potential between strands of different heights in the slot, different inductive reactances and hence unequal currents in the strands. For single turn bars, Roebel transpositions in the cell portion are most common, ranging from 360 to 540 degrees for most applications, although NEC has manufactured bar Roebel transpositions as high as 900 degrees. The transposition virtually eliminates circulating current losses in the coil by ensuring that each strand occupies the same height position, for the same distance, as every other strand. See Fig. 4.

The Roebel transposition is very efficient in reducing circulating currents, as well as lowering manufacturing costs. While the 360 degree Roebel transposition is most common, longer core lengths can accommodate a more efficient 540 degree Roebel transposition. Higher degree Roebel transpositions as mentioned above, can be incorporated by adding transpositions in the end turns.

Roebel transpositions in the cell length are not new, but do represent a significant improvement over previous methods of transposition designed to reduce circulating current losses. These older methods included the lead group transposition and the strand by strand transposition (Fig. 5.). Both methods require more precision at site during the field winding process, and many older machines with these types of transpositions suffer from strand short circuits. The author’s
company, as part of a stator rewind in Africa, converted the existing strand by strand transposition to a Roebel bar transposition, and completed the on-site rewind in record time. A sister machine, rewound by the Original Equipment Manufacturer (OEM), retained the strand by strand transposition. That machine failed on startup due to strand short circuits in the connections, and the author’s company was asked to step in and rewind that sister machine at that point – with the same Roebel bar transposition enhancement (Fig. 6).

Fig. 5 Strand by strand transposition. In this design, the OEM did not convert the strand by strand transposition. The stator failed on startup.

Fig. 6 Conversion to Roebel bar transposition by NEC allows solid clip connection. It has since operated successfully for many years.
Transpositions in multiturn coils are typically handled by a 180 degree twist in one of the turns. (Fig. 7). This twist inverts the conductor strands for the remaining path of the coil, so the same effect of circulating current reduction is accomplished. The placement of the twist is critical to effecting the loss reduction. This is a point the designer must take into account.

![Fig. 7 Twist in Multiturn Coil](image)

**Strand Size and Arrangement: Multiturn Coil versus Single Turn Bar**

Over the last forty years of generator design, it has been typical for multi-turn coils (Fig. 8) to be used in small, lower rated, steam turbine-driven generators and also in hydrogenerators up to about 100 MVA in rated output. In larger steam turbine driven generators and hydrogenerators rated higher than 100 MVA, a single turn bar winding is more often used.

![Fig. 8 Full Loop Multiturn Coil](image)

Both Single Turn Bars and Multiturn Coils are made up of copper strands with strand insulation and groundwall insulation. Multiturn Coils have individual turns, often with dedicated turn insulation, while Single Turn Bars of course do not. Multi-turn Coils also have two legs or cell sections, making a complete loop, while Single Turn Bars are typically “half-coils.” Two “half-coil” bars make a complete coil. Multiturn Coils are most often utilized in hydrogenerators, with short core lengths and many stator slots, while bars or half coils are most often used in larger turbo generators with long length cores and fewer stator slots. The full loop Multiturn Coil becomes more economical to handle and wind when applied to hydrogenerators with many slots, but bars are significantly easier to remove and replace than Multiturn coils – irrespective of the number of stator slots. Likewise on large turbo-generators, Single Turn Bars (Fig. 9) or half coils are much easier to handle than a full loop coil would be.
When rewinding, the option does exist to change a multiturn coil to a single turn bar. Some owners are choosing this option more frequently, since the turn insulation can be a weaker area in the coil design and winding failures are often due to a surge and failure of the turn insulation. The choice of a Multiturn Coil or Single Turn Bar is often dictated by the owner, perhaps based on previous bad experience, such as an untimely failure.

Although rewinds can include a new core with much better core steel material, an increase in flux density in the magnetic circuit, may also result in higher field current, heating and losses. Multiturn coil design provides more flexibility in accommodating these flux increases compared to designs with a single turn bar. Some negative aspects of the Multiturn Coil design include the risk of turn insulation failure, as well as “top strand heating.” Top strand heating results from eddy current losses that are greater in the top strands. For bars, this is not an issue due to the high radial thermal conductivity with the Roebel type transposition.

Top strand heat transfer in a Single Turn Bar can be up to 500 times better when compared to the same type of heat transfer for a Multiturn Coil. Therefore, the top strand heating is not an issue for Single Turn Bars. Top strand heating is higher with small air gaps and top strands closer to the main flux. A good rule of thumb is if top strands are located less than half of the slot width from the air gap, then Single Turn Bars - or an alternative method of effective turn transposition in Multiturn Coils should be used.

In slow-speed hydrogenerators with many slots – an overlooked advantage of a Single Turn Bar winding is the fact that any coils that fail during the rewinding process can be easily removed compared with a lap-wound Multiturn coil winding. Depending on the location of the bar requiring removal – and the specifics of the rewind procedure – a Single Turn bar replacement will generally occupy a fraction of the time required to replace a Multiturn coil. The latter often requires removing numerous coils before the required coil can be removed, and the removal of the healthy coils often means that they have to be discarded and replaced anyway. This advantage of Single Turn bar windings on slow-speed machines with many slots can make a rewind considerably quicker than the Multiturn Coil design it replaces.
The designer has to be proficient and experienced in many aspects of rotating electrical machines in order to approve and propose a Single Turn Bar winding to replace a Multiturn coil winding. An example of this is the fact that a Multiturn winding will by design have many more parallel circuits than a Single Turn bar equivalent. This will cause an increase in Unbalanced Magnetic Pull (UMP) in the Single Turn Bar would machine and could lead to excessive rotor vibration.

**Uprating**

It often is possible to uprate the generator to a higher output (MVA), as part of a rewind/refurbishment project. Older generators often can be uprated by larger increments, since their old insulation is less efficient, having lower dielectric strength compared to more recent advanced insulation technology. Stator bars or coils manufactured with shellac mica, asphalt, and even polyester, can be upgraded to more advanced epoxy mica glass materials. The newer insulation is mechanically stronger and can allow more copper to be placed into the slot. This decreases copper Joule ($I^2R$) losses, and combined with other design enhancements, can result in significant increases in output on the order of 10% to 50% of rated MVA for some very old machines. Most owners state a specific operating dielectric stress level VPM (Volts per Mil or kilovolts per millimetre) in the specification to keep the high voltage coil suppliers on a level playing field. A value of 2.65 kV/mm (65 VPM) is a common specification requirement that balances maximum performance with long term reliability. A higher value may appear attractive in the proposal evaluation since it will allow a higher output, but long term reliability is jeopardized, and of course premature failure of the bar or coil is more likely since the insulation is stressed more heavily.

**Global Vacuum Pressure Impregnation (GVPI) versus Bar VPI (BVPI) versus Resin Rich / B-Stage**

The stator winding manufacturing insulation scheme, whether Global VPI, Bar VPI, or Resin Rich / B-Stage, is often based on the manufacturer’s facilities and experience. The basic differences are the following:

- **Global Vacuum Pressure Impregnation (GVPI):** The entire stator is vacuum pressure impregnated. The system, when implemented properly, is efficient, low cost and reliable. One drawback involves the repairability of the stator winding should a bottom coil fail. Although repairs are possible, rewinding a GVPI stator winding is very difficult – more difficult than a BVPI winding.

- **Bar Vacuum Pressure Impregnation (BVPI) (can be referred to as single coil VPI):** Each individual bar or coil is vacuum pressure impregnated. The resin impregnated coil is then cured and the hard coil is installed in the stator core. With this process, epoxy resin is driven into the coil and tape. A vacuum is pulled first, and then Nitrogen gas is applied under pressure. This process can be more expensive than the other two systems, since large Vacuum Pressure Chambers and large amounts of epoxy resin are necessary; furthermore, custom made steel dies are precisely machined for each finished size. When implemented well, the bar or coil is essentially void-free with very low Power Factor or
Dielectric Dissipation Factor (Tan Delta) measurements. This system also has the advantage that should an individual bar or coil fail, it can be removed and replaced without damaging the core or requiring an entire rewind.

- Resin Rich/B-Stage – This insulation system uses insulating tapes that are already pre-loaded with epoxy resin. When applied and heated, resin flows, and with pressure and temperature the insulation is eventually cured. Well-manufactured bars or coils with this system utilize expensive autoclaves for applying the correct pressure for forming the coil to the desired shape. Often, however, industrial workshops manufacture coils with this system utilizing inexpensive equipment that results in poor quality bars and coils.

Most owners, end-users and specifications allow both BVPI and Resin Rich / B-stage replacement windings, since if manufactured correctly by high quality high voltage coil manufacturers, performance is comparable. GVPI windings are common on new machines but rarely used on rewinds.

### Core and Number of Slots

Unless the core is being replaced, and options are on the table to change the number of slots, all bar or coil rewind designs must function within the existing parameters of the stator core. This means that the core length, core diameter, number of slots and slot size remain fixed. The design of the coil in the slot can indeed be changed to increase output (MVA). This can be accomplished primarily by increasing the copper content (cross-sectional area) and changing the number and size of strands. Overall stator winding losses can also be affected by changing the “mean length turn.” If the core is replaced, which is common on older hydrogenerators, options to change the number of slots are possible. Changing the number of slots can improve output, efficiency, and even reliability of the refurbished machine. A change in the number of slots can often allow the conversion from a Multiturn coil winding to a Single Turn Bar winding, where this would not be the case with the same number of stator slots.

### Corona Suppression System

There are different styles of Corona Suppression Systems (CSS) in the industry today, varying only by the number of different high voltage bar or coil suppliers and materials available in the market. Primary choices include paint or tape systems in the bar or coil cell portion, and the same in the transition area moving into the end turns. A well-tested system that is compatible with the existing groundwall insulation and slot packing system is essential. A common issue with many suppliers is in the transition area between the semi-conductive material in the cell and the stress-grading (gradient) material in the cell bend just outside the core. Corona burning causing degradation of the CSS can occur, requiring regular inspections and maintenance to maintain reliability.

Corona Suppression Systems that are paint-based are typically less expensive and easier to repair but can be more easily scratched and damaged. Systems that are taped-based are more expensive and more difficult to repair, but more resistant to scratching and damage. The
author’s company has developed a CSS that includes both paints and tapes. The System has been VET (Voltage Endurance Tested), blackout and UV (Ultra Violet) camera tested, and proven to be compatible with our own insulation design.

**Slot packing**

An effective slot packing system must hold the bar or coil tight in the slot, free from excessive vibration and looseness that can lead to slot discharge and vibration sparking. Again, there are many options available, but a tried and tested system for many decades is the use of semi-conductive side ripple springs. (Fig. 10). This system, used by the author’s company for over 30 years, includes insulating springs that are compressed when the bar or coil is installed into the slot core. This pre-loads the spring, similar to a Bellville washer. The pre-load keeps the bar/coil pressed tight against the core slot, even after many years of operation, when insulation and top fillers and wedges shrink and the bars or coils have a tendency to become loose in the slot. Side ripple springs are semi-conductive, using carbon black to promote grounding of the coil surface to the core. Other systems such as flat side and round packing promote tightness initially, but can become loose over time. Global VPI windings will develop cracks in the resin between the coil and the core if not properly packed with shear stress relieving surfaces. Similarly, top ripple springs are commonly used to provide radial pressure on the bar or coil in the slot, to keep it tight. These do not have to be semi-conductive since there is no radial path to the core ground.

![Fig. 10 Semi-conductive side ripple springs next to bars in slot.](image)

**End Winding Bracing**

Not to be forgotten is the importance of end winding bracing on the installed bars/coils. Severe damage to the stator winding can occur during transient faults, if the end winding is not braced and supported properly. Likewise, changes in temperature from cold, startup conditions - to hot, full load conditions - create thermal stresses on the winding, which must be managed. A bracing
system that provides radial support of electromagnetic forces, but allows axial expansion from temperature changes, is most effective. These types of systems are expensive and are not always included in the original equipment due primarily to cost controls or even lack of design knowledge. A rewind provides the opportunity to include this important system, which is a choice the owner should make to improve long term reliability.

Case Histories

N’zilo Hydroelectric Alternator Stator Rewind – Katanga Provice, DRC

NEC’s authorised service provider in Africa, consolidated its role as an integrated electrical and mechanical services provider for the power generation and other industries in Africa, with a contract at the N’Zilo Hydroelectric Power Station in the Katanga Province of the Democratic Republic of the Congo (DRC), operated by State electricity utility Société nationale d’électricité (SNEL). The contract included the stator rewind of a 30 MVA 18 pole vertical AC synchronous alternator. Although small by global standards, the N’zilo Station forms a critical component of the power generation network in Katanga and the entire DRC, where electricity supply in general is under severe pressure.

Located on the Lualaba River, N’Zilo was commissioned in 1958 to provide power to copper mines in the nearby Kolwezi region, but has only been intermittently operational since then due to ageing infrastructure. While Units 2 and 4 were refurbished, after 40 years of successful operation - Unit 3 recently experienced a stator failure that necessitated urgent repairs. The DRC suffers from a severely limited electricity grid, which is of critical concern to the mining industry in particular.

Marthinusen & Coutts was recommended to SNEL by Katanga Mining due to the strong partnership that has formed between the two companies over the years, and in particular the very challenging but successfully completed refurbishment of the SCK 70 MVA synchronous condenser, also discussed in this paper.

N’zilo’s Unit 3 Alternator stator winding was of the Multiturn coil type, and although an enhancement to a Roebel transposition Single Turn Bar winding was possible – aspects existed that did not make this a viable option at the time. Despite very challenging logistics and a very remote site location – the Multiturn coils were dispatched to site in excellent condition, resulting in a successful rewind using many of the enhancements discussed in this paper – in particular, side Ripple Springs. The Unit has been in successful operation for some time at the time of writing this paper.

70 MVA 8 pole Synchronous Condenser Refurbishment, SCK1, Katanga, DRC

Marthinusen & Coutts also completed refurbishments of two 70 MVA 8 pole synchronous condensers for SNEL at their converter station in Kolwezi, Katanga Province. The stator Single Turn bars were imported from National Electric Coil (USA). A modular arrangement was adopted due to the size of the machines, with sub-assembly taking place on site. The
refurbishments entailed stator rewinds, as well as rotor rewinds and several complete new pole assemblies. The synchronous condensers are critical components of the SCK DC to AC converter station in Kolwezi in the DRC. Power is transmitted from Inga hydro-electric Power Station in the north, and converted from AC to DC. This is then transmitted to Kolwezi and converted back to AC, with the power feeding the energy-intensive copperbelt in the Katanga Province.

The synchronous condensers supply the necessary reactive power, which cannot be transmitted via the DC transmission line nor provided by the converter station. The inertia of the rotating assembly of the condenser provides the necessary energy to stabilise the power system in the region, which aids the overall stability of the grid. The condenser has a stator inner diameter of 2.4 m and a core length of 3 m, while the rotor weighs 95 t and the stator weighs 98 t. This immense weight and size meant that an on-site solution had to be provided for SNEL. Challenges included the total lack of facilities on site, with no access to either cranage or workshop facilities.

Although power uprating was not required – the new stator bar design allowed an efficiency improvement and lower operating temperatures, at the original 70 MVA (12 kV) rating. Side Ripple springs were also used on these stators, together with bars individually manufactured for the various connections on the stator – resulting in a finished product superior to the original, even just by appearance. The project also included identifying and designing a method of ruling out the primary failure mechanism on the rotors of the condensers, which was movement of the damper cages over time (Fig 11).

![Fig. 11 The result of damper cage movement on SCK 70 MVA Synchronous Condenser Rotors. The failure mechanism was rectified after more than 35 years of operation with this condition.](image-url)
Kelvin Power Station 75 MVA Emergency ‘Patch’ Repair of Stator Bars

This project involved replacing six Roebel bars of a 1960’s vintage 75 MVA Synchronous Alternator. The unusual aspect here was the fact that the stator is of the Eickemeyer design – often referred to as a ‘Butterfly’ winding. Due to several constraints – the end-user required an emergency ‘patch’ repair. The spare bars were air-freighted from NEC to South Africa, and fitted in a painstaking process only partly conveyed in the photos below. Individual strands had to be brazed in the most constricted locations, with the end result appearing considerably better than one would have expected for such a patch repair. The interesting fact about this stator is that the insulation wall thickness matched that used today for the same voltage – yet the stator has been in operation since 1964!

Fig. 12 and 13 Kelvin Power Station 75 MVA Turbogenerator Stator with Eickemeyer Winding and Stator Repair in Progress

A graphic model of this unusual winding design is shown in Fig. 14 below.

Fig 14. NEC Graphic Model for Repair/Replacement Stator Winding
Conclusions

It is important that owners and end-users realize that they can have a lot of influence over the design and manufacture of new stator bars and coils, both for new units and re-winds. A very experienced and skilled service provider is required to guide owners and end-users who are not proficient with all the technical issues involved, but choices dictated by the owner or end-user can affect quality, schedules, and long term reliability. Key decisions include whether to ask for bars or coils, Bar VPI or Resin Rich, transposition details, uprated power (MVA), Corona Suppression Systems, and end-turn bracing upgrades. Each of these decisions plays a crucial role in the final design, manufacture, installation, testing and ultimate successful operation of the stator winding. It is also important for owners to be sure of the capabilities and experience of the service providers involved. This will ensure that the most advanced technology improvements are incorporated into the redesign, and that any unusual challenge is met.

References

1. Eddy Currents in Large Slot-Wound Conductors, A. B. Field. AIEE Transaction, volume 24, 1905, pages 659-86.


