Generator Spare Conductor Bars

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Abstract — **Turbo-generator stator spare bar policy needs careful evaluation considering its potential influence on unit availability in the event of a winding failure. This paper intends to summarize stator spare bar issues, starting from the initial procurement decision up to and through storage and test routines, based on experience with different types of turbo-generators.**

I. Introduction

THIS paper applies mainly to large cylindrical-rotor synchronous generators (turbo-generators) driven by steam turbines or combustion gas turbines. The stator winding of these machines is usually designed in two layers, including in each slot one top (nearest the wedge) and one bottom (farthest from the wedge) conductor bar. Each insulated conductor bar is made up of several parallel copper strands (sub-conductors) as in Fig. 1. It includes a middle straight part installed in the slot and an involute shaped end-winding (Fig. 2).

After installation in slots, the bars are serially-connected to form coils and the entire winding. At low and medium outputs, the conductors are indirectly cooled by gas (air or hydrogen). The higher-rated turbo-generators have stator windings directly cooled by gas or water flowing in hollow strands (Fig. 1).

Fig. 1: Typical turbo-generator stator bar cross sections. Left to right: conventional indirect cooled (air or hydrogen), inner hydrogen cooled, and water cooled.

Fig. 2: Both the straight section that fits into the slot in the core iron and the involute that extends beyond the core iron are visible on these coils.

II. Spare Bar Availability

Individual stator bars or entire stator windings may need replacement depending upon the severity and extent of the failure. The replacement reasons include various winding deterioration mechanisms that typically end up in a winding ground fault. These failure mechanisms include such items as spark erosion, short circuits, extensive partial discharge activity, high end winding vibration, insulation aging, strand shorting or fatigue cracking, to name a few. Water-cooled windings can experience additional faults, such as leakages or blocked hollow strands. Also, stator core failures often require stator bar replacement [1].

The generator stator can be partially or fully rewound, if a bar or winding failure occurs. The decision depends on the extent of the failure damage, budget and spares availability, outage duration restrictions, operational and maintenance history, desired reliability improvement or life extension, dielectric test results, and so on. A total rewind will normally permit an upgrade of the winding insulation, slot and end-winding support, and wedging system. It can offer additional benefits, such as increasing the generator output and its efficiency or solving hazardous material issues like removing old asbestos-based insulation.

According to a manufacturer's survey, [2] the most probable age for a stator rewind is approximately 35-40 years for hydrogen-cooled machines. For water or air-cooled windings, it is typically one decade shorter (25-30 years). This takes into account that the winding life is influenced by many additional factors, such as how the unit is operated. An EPRI survey [3] mentions that the majority of stator rewinds are actually performed on younger generators (15-18 years old).

A stator bar failure is a significant event, requiring immediate resource mobilization and repairs to minimize the extent of generator output interruption. According to EPRI [3], the average stator rewind time is about 6-8 weeks, from initial unit shut-down to restart. This time frame does not include the up-front lead time to manufacture replacement stator bars, and therefore the total forced outage time will be much longer if suitable spare bars are not available in sufficient quantity for the repair.

Conversely, if a scheduled generator stator rewind is well-prepared beforehand, and the stator bars have been procured in advance, it is possible to complete the bar replacement in 30 days or even less [4]. Therefore, the ready availability of spare bars, after a winding failure occurs, can reduce total forced outage time significantly.

In addition to in-service stator bar failures, individual bar failures occur occasionally during routine outages over voltage maintenance tests [5]. This is another reason to keep the right quantity of spare bars available.

III. Spare Bar Investment

Each power generator should develop its own generator spare bar strategy. The cost benefit to be gained by the holding of spare bars is influenced by many factors including the number of identical generators in the owner's fleet, the probability of a spare being needed and the likely delivery times. The investment effectiveness can be calculated in different ways. Widely used simple methods are *payback period* or *revenue requirement* method [6].

Whatever method is used, the spare bar capital investment cost versus the outage cost (i.e. extra expenses and revenues lost as a result of bar failure) must be evaluated and compared against one another. The calculation is also affected by the estimated stator winding failure rate and generation unit outage time per failure. These data are obtainable from large population statistical reports, like NERC/GADS (North American Electric Corporation / Generating Availability Data System), technical papers and short courses [7] about known generators / insulation issues, and the plants' previous experiences with specific machines or manufacturers.

The spare bar price contains the fixed costs (tooling, engineering, project management) and the production costs (material, manufacturing, packing, etc.). Fig. 3 shows an example of total budget dependence by the number of purchased spare bars.

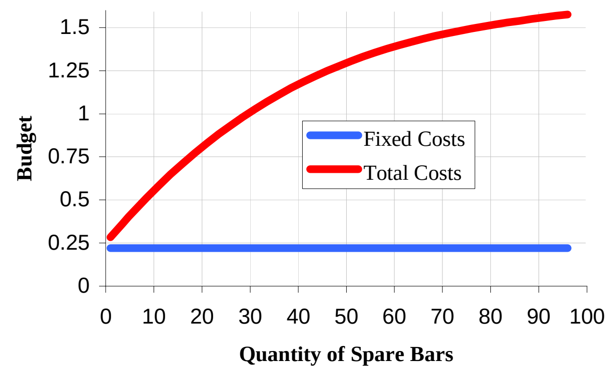

Fig. 3: The above chart plots the cost of spare bars against their quantity.

IV. Spare Bar Quantity

Significant differences can be found among various spare bar policies around the world. According to CIGRÉ and EPRI data, [8]-[10] the spare bar typical quantities range from a minimum of one-sixth of a top bar set with 3 bottom bars, to a maximum of a complete spare bar set including all winding supplies for a full rewind. Extreme and unusual policies are to not stock in inventory any bars and to entirely depend on the manufacturer for original bars. Many current specifications frequently specify either 1 top and 1 bottom bar, or 2 tops and 2 bottom bars.

Ideally, a complete spare bar set would enable the most comprehensive response if a forced outage occurs, but this scenario often cannot be cost justified, unless the owner has multiple identical units. If a top bar fails, its replacement often involves removal and possibly replacement of adjacent bars on each side of the failed top bar. If a bottom bar fails, it will be necessary to take off a number of top bars to permit its removal (Fig. 4). This is further described below.

Fig. 4: Top bars mounted over bottom bars.

A. *Top Bars*

The number of top bars required to be removed in order to replace a damaged bottom bar is equal to the coil span (pitch) plus one [11]. Normally this *coil* span value is smaller than the *pole* pitch (*short-pitched* generator windings are advantageous in shortening the end turns and reducing harmonic effects in the machine).

The recommended stocking quantity of top bars for water-cooled generators is slightly higher, close to or equal to the pole pitch value [12].

B. *Bottom Bars*

The number of required bottom spare bars is normally much lower, between two bars [13] and up to four bars in case of water-cooled generators [12].

C. *Generator Winding Design*

The above-mentioned bar quantities can be only used as a preliminary approximation. The spare bar issue should take into consideration many other aspects, the first one being the influence of generator design.

In a typical stator bar design, most top bars are identical in size and shape. Likewise the same for most bottom bars. Only a few bars being used for connection to the line and neutral terminals have differences. This kind of bar standardization allows a minimum of spare bars to be kept in stock, for many situations.

However, there are generators that include several different shapes of bottom and top bars. For instance, the water-cooled stator of one manufacturer has 60 slots and includes 10 different shapes of top bars and 10 different types of bottom bars. Keeping suitable spare bars for such a generator requires a huge investment with the possibility of no return on that investment. Preparation for a worst-case contingency will involve a minimum stock of 10 bottom bars (one of each type) and 30 top bars (3 of each type).

The following examples emphasize the influence of different designs on spare bar policy. All examples are generators that have 2 poles, are water-cooled and are equally rated at 22 kV, 650 MVA:

1) Generator A has 48 slots and is made in Europe. Its coil span is 20. There are two types of bottom bars, 42 *normal* bars and 6 *connection* bars. Similarly, there are 42 *normal* and 6 *connection* top bars. The required worst case spares for this generator will be: 21 *normal* plus 3 *connection* top bars, 2 *normal* plus 2 *connection* bottom bars, i.e. a total stock of 28 spare bars.

2) Generator B has 42 slots and is manufactured in USA. Both the top and bottom coils are of 7 different types (6 *series* types plus one *phase* type), in quantity of 6 bars from each type. The coil pitch is 18. This generator will require 7 bottom spare bars (one of each style) and 21 top spare bars (3 of each style), i.e. a total of 28 spare bars.

3) Generator C has 42 slots and is made by another American manufacturer. It includes 36 *normal* plus 6 *connection* bottom bars, 36 *normal* plus 6 *connection* top bars. The coil pitch is 17. For this generator, 25 spare bars (18+3 tops and 2+2 bottoms) should be purchased.

D. *Generator Cooling Design*

Another design influence is the cooling system. For instance, a common design of water-cooled generators uses hoses connected through clips to every winding bar (Fig. 5). However, there are also other designs that use water-boxes made from insulation material, supplying cooling water to a large group of bars (Fig. 6). This design has bars of many different shapes.

All things being equal, the more complex bar designs deserve more spare bars available. Procurement lead times for new water-cooled bars, or hydrogen inner-cooled bars, are significantly longer than conventional hydrogen- or air-cooled windings.

Along the same lines, spare bar availability should be more strongly considered for higher-rated units, which have considerably higher lost revenue costs, if unavailable.

Fig. 5: Water-cooled stator using bar clips.

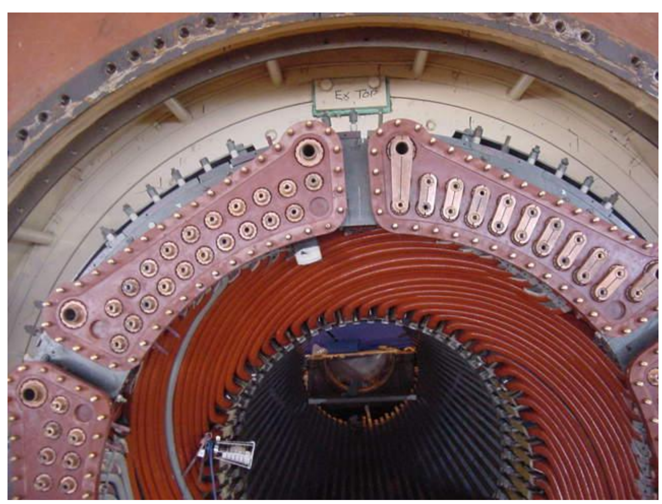

Fig. 6: Stator cooling design using water boxes.

E. Bars Reusing Expectancy

Assuming a bottom bar failure, the quantity of top bars stocked depends also on the likelihood of reusing them after their removal from the stator. Bars can suffer distortion or damage during removal because of their tightness in the slot after many years of service. Lack of care when dismantling water-cooled bars can lead to damage of the hollow copper strands. Carefully removed bars may be suitable for refurbishment and reuse, but oftentimes they must be replaced by new ones. The safest strategy is to keep in stock the spare bar quantity as recommended in the previous section.

F. Other Aspects

Other influences on spare bars quantities are: age of the unit, operational history (based-load or load cycling, number of start-stops), past inspections and tests results, number and type of generators in the fleet, maintenance standards, desired level of reliability, risk tolerance.

Also it is important to note that generators from the same manufacturer and the same series or type may contain slightly different original bars that are not fully interchangeable. Do not automatically assume that sister units have the exact same stator bar that is interchangeable, especially if the units were manufactured and installed at different time periods. It should also be noted that manufacture of additional spare bars well after the initial winding installation, may introduce variations in tooling and setup that could cause interchangeability issues.

Special interest should be accorded to the air-cooled, global VPI generators. The fully wound stator of these machines is vacuum-pressure impregnated as a single piece. The replacement of stator bars in the field can be a difficult and risky task. While removal of the existing individual bars is possible, there is potential risk of damaging the stator core in the process. In these generators, replacement of a top bar involves many destructive efforts such as cutting of the end-winding and individually removing bar strands and slot insulation. Normally if a bottom bar fails, the entire winding has to be burned out and the stator completely rewound. For this reason, only very few top spare bars may be necessary; keeping bottom spare bars seems needless for such generators.

V. Spare Bar Specification

New or refurbished bars should be carefully specified in order to assure their quality for long-term storage and satisfactory operation when installed inside the generator. They should be supplied as part of a planned rewind or purchased to be stored long term for any future occurrence. The overall design of the spare bars should be fully interchangeable with the original bars.

A few well-formulated threshold requirements are recommended to be included in the specification, in order to verify the manufacturer experience with similar generators (i.e. having the same or higher rated voltage, same cooling method, same or higher output). The bidder should be required to submit detailed reference lists with the proposal, pointing out user names and contact details.

A good specification should also include important data, for example: machine rating (continuous and peak capabilities), stator cooling details, insulation system requirements (e.g. insulation class), etc. The specification should state the manufacturer's responsibility in providing bars suitable for use in the existing generator. This is because the purchaser is typically not able to specify essential dimensional requirements of the unit. Instead, these data have to be responsibly obtained by the spare bar manufacturer.

The specification should require that all records relating to tests of any individual bar be traceable by serial number to that bar [14]. Special attention should be paid to required routine tests (or acceptance tests) of the finished conductors. The spare bars should be factory tested identically to those being used in the generator. Some requirements are detailed below:

1) The bars should be factory tested for their power factor (tangent delta) and power factor tip-up (delta tangent delta) according to relevant standards [15], [16]. These tests serve to assess the uniformity of manufacture as well as to determine the dielectric behavior of the insulation.

2) The slot main ground-wall insulation should be power frequency high potential (hipot) tested at 1.3(2E+1) for 1 minute [17], where E is the line voltage of the machine[1].

3) The water-cooled conductor should additionally withstand flow tests and be free from leaks, checked by pressure and vacuum tests.

VI. Spare Bar Manufacturer

Competitive bidding for spare bars can be technically and commercially valuable. It is important to note, however, that the best time to procure spare bars is at the time of the original generator purchase, or at the time of a stator rewind involving the complete set of bars. At this point in time, interchangeability of spare bars with the original set is assured.

The original equipment manufacturer is advantaged in spare bar offerings, because it is the owner of full information and forming tools. Non-OEM manufacturers may be disadvantaged by unavailability of bar data, but they also have worthwhile solutions. For the non-OEM, the reverse engineering of stator spare bars is based on detailed machine measurements (a *measurement outage* with rotor out should be arranged for this purpose) and will further include design, tooling and fabrication steps. If old spare bars already exist in the owner's storage, the non-OEM can measure and analyze them, with this information being utilized for the new bar design.

In order to deal with these difficulties, several solutions are practiced by non-OEM's: offering measurement services during normal planned major outages, further proposing engineering analysis / design, tooling manufacturing and bar prototype manufacturing / testing [18], and using dedicated processes for measurements in the field. [19]

[1] All hipot tests in this paper refer to 50 or 60Hz tests, 1 minute. In case of agreement for alternative DC tests, the mentioned AC values shall be multiplied by 1.7.

It is advisable that the purchaser visit the factory during the manufacturing process to witness the tests or geometry verifications in a mock (dummy) stator core (Fig. 7).

If the purchaser has no previous experience with a new supplier, a sample bar insulation test (voltage endurance test) may be required. If agreed, this test is usually carried out on sacrifice bars per IEEE 1043 and 1553 [20].

Fig. 7: Mock dummy stator core used to test fit stator bars during manufacturing.

VII. Spare Bar Storage

Optimal spare bar storage conditions are essential in safekeeping the bar investment value.

The spare bar shape requires specially-designed wooden boxes to be used for transport and storage. Inside the box, each bar should be adequately supported to prevent sagging and wrapped in plastic with desiccant taped to bar ends [21]. The packed bars shall be stored in a closed, dry and clean storehouse.

Improper packing or storage conditions can cause humidity absorption, dust contamination, worn or broken insulation through abrasion, scratches or damage to copper strands. Fig. 8 shows examples of spare bars found defective following unsuitable storage conditions.

Usually, the damaged bars can be refurbished or reinsulated. Complete replacement of the bars insulation can typically be done using the old copper conductors.

Fig. 8. Spare bars damaged during storage.

VIII. Spare Bar Tests

Normally it is not required to test the spare bars periodically but only to check the exterior condition of the storage box visually.

However, the spare bars should be carefully tested before their installation inside the generator stator. The spare bars should be visually inspected and tested including DC insulation resistance and power factor (up to line voltage). In addition, the bars' cross section should be measured to prove their suitability for installing in given slots. Inner-cooled bars, whether cooled by air, hydrogen or water, should be tested to assure that no blockage in the hollow conductors or vent tubes is present.

One of the most important tests for spare bar suitability is the hipot test. The test voltage depends on the work scope (full or partial rewind) and on the test voltage values intended for use at different work stages. During the winding installation, the individual bars and winding parts have to be tested at various times, at decreasing voltage levels, until the final acceptance test.

Fig. 9. Testing of stator bars.

The most demanding spare bar hipot test (Fig. 9) is for a full rewind using all new bars. This kind of work requires a final AC (or DC Equivalent) test identical to that performed in a new generator, at 2E+1 for 1 minute [22], [23]. One example of a typical hipot sequence is the following:

1) Individual spare bars in the factory: 1.3(2E+1)
2) Individual spare bars after storage: 1.2(2E+1)
3) Bottom bars installed in the core: 1.1(2E+1)
4) Complete winding after wedging: 2E+1.

In the case of a partial rewind, which uses a combination of new and aged installed bars, lower level hipot values are normally required. The final AC test after finishing the work should be between 1.25-1.5E, the same as for periodical maintenance dielectric tests [24].

In-between the above mentioned extremes, the machine owner and the winder should agree on the hipot test value.

IX. Spare Bar Additional Issues

Generator rewinds should be performed by well-trained and experienced personnel, using dedicated tools and special materials. Some complementary materials (insulation tapes, resins, etc.) have a short shelf life and are not practical for long-term storage.

Other alternative solutions can be considered instead of keeping spare bars in stock, to minimize investment costs. These options can further reduce the risk of an extended forced outage due to a winding failure, but at the same time minimize the investment cost necessary to reduce this risk. One possibility is to purchase only the copper required for strand manufacturing, instead of complete insulated bars. This represents a considerable advantage in the case of specialized hollow conductor, whether copper or stainless, due to longer lead times to obtain this material.

Some manufacturers offer partially-manufactured conductor bars up to the point where they become specific for a given location in the stator. These are partially insulated only along the slot section. Other manufacturers sell bars not hardened in the end-winding portion, to be finalized only at the time of mounting inside the slots. This flexibility can be advantageous during installation.

A complete spare stator, including iron core and winding, can be a useful alternative solution, but very expensive. This solution can be justified in the case of many identical generators with a known high incidence of stator iron damage or for the case of owning multiple Global VPI machines.

It should be noted that the purchase of spare bars after original winding installation is not ideal, due to the difficulty in matching and nesting new bars to the old bar's shape. The ideal time to procure spare bars is with the original machine order or as part of a rewind project, in which the entire stator is being rewound. In each case, spare bars are provided at the same time a complete winding is manufactured. This assures the best fit and that the spare bars will be interchangeable with the existing winding.

Stator bar reinsulation (reference Fig. 10), is a viable method of quickly returning the generator back to reliable service.

Fig. 10 Stripping of ground insulation in preparation for reinsulation of the stator bar. This is a method of quickly returning the failed or damaged bars back to service if spare bars are not available. This method is not possible if bars are severely damaged.

In this option, the damaged ground insulation is stripped and re-applied. This can be done relatively quickly, especially when compared against longer lead times with manufacturing hollow conductor for water-cooled coils, vent tubes for inner hydrogen cooled bars, other long lead components. As mentioned earlier, however, coil removal must be done carefully to avoid causing internal shorts.

X. Conclusion

Spare stator bars are important to the long-term reliability of any generator. In many cases, owners have some amount of original spare bars in stock or have ordered additional spare bars as part of a rewind. In many other instances, however, spare bars are not currently available should a generator winding forced outage occur. This paper attempts to describe the issues related to spare stator bars, including emphasis on the importance of owning spare bars, as well as highlight the complexity of knowing how many spare bars to have on hand. The paper also describes various aspects and examples regarding spare bar quantities and types, their specification and procurement, storage and testing.

The generator owner should decide on a spare bar policy for each generator in its fleet. The type and number would be influenced by the subjects discussed in the body of this paper, including the generator design, rating, cooling method, bar shape, connection method, industry failure rate[25], age, and expected operational duty cycle.

Stator bar manufacturers can provide assistance with recommendations for the number and type of spare bars needed for long term reliability. However, knowledge and understanding of all the issues related to this important subject should be key to the owner's generator availability plan.

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