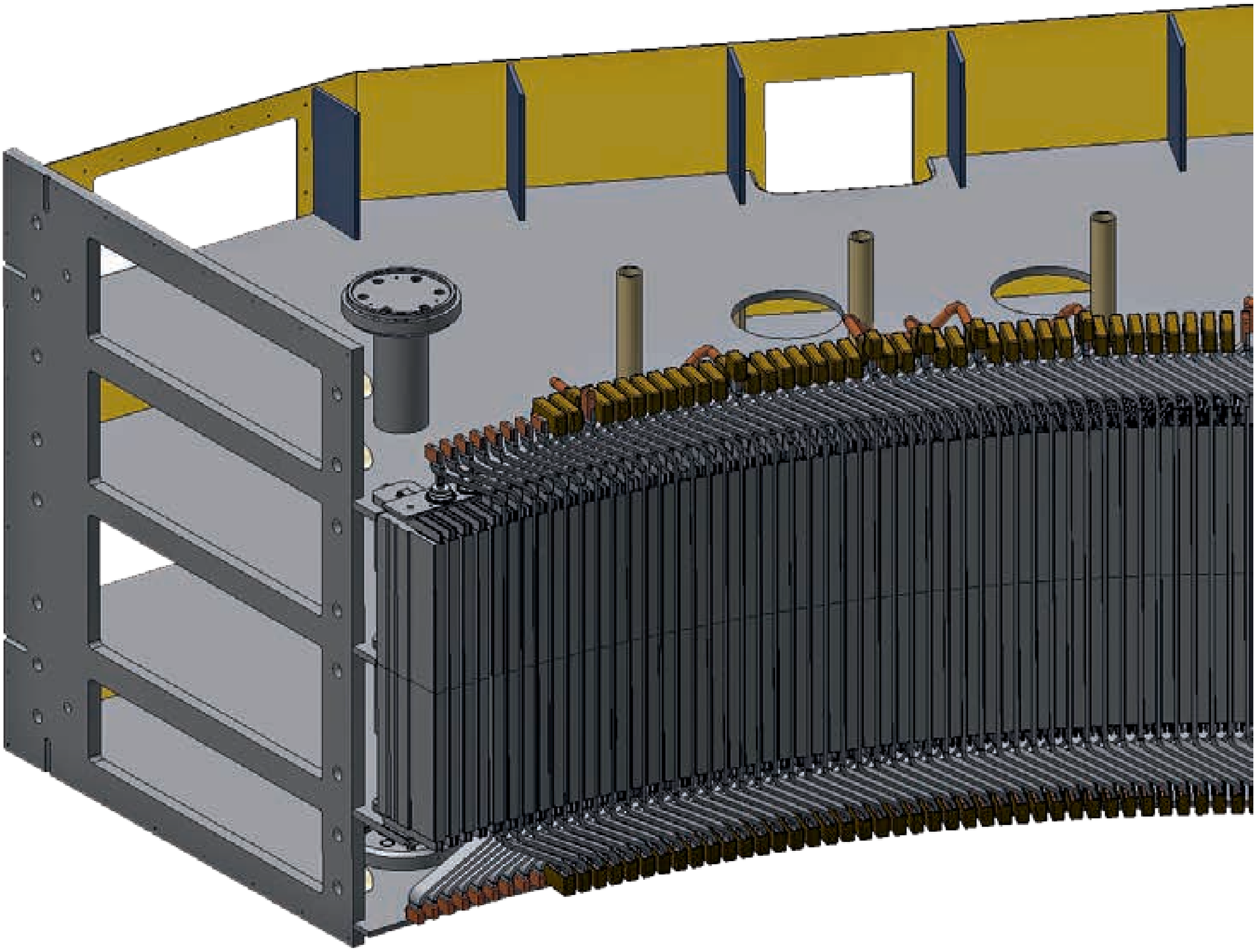


Advanced 3-D windings

GMD 3-D windings with just a few clicks

MACARENA MONTENEGRO-URTASUN, GIOVANNI CANAL, JAN POLAND, AXEL FUERST – Gearless mill drives (GMDs) are produced individually according to customer specifications and so are not available as an off-the-shelf product. According to IEEE, 33 percent of all failures, and the consequent exorbitant downtime costs, detected on large motors such as these during normal operation are related to the stator winding. ABB has introduced a 3-D winding design philosophy that allows different winding layouts to be evaluated and compared, offering a solid base for analysis and solution choice. This translates into reduced manufacturing costs, faster site installation, shorter repair times and a lower risk of winding failures due to poor design.

1 Flow diagram for the 3-D winding design process

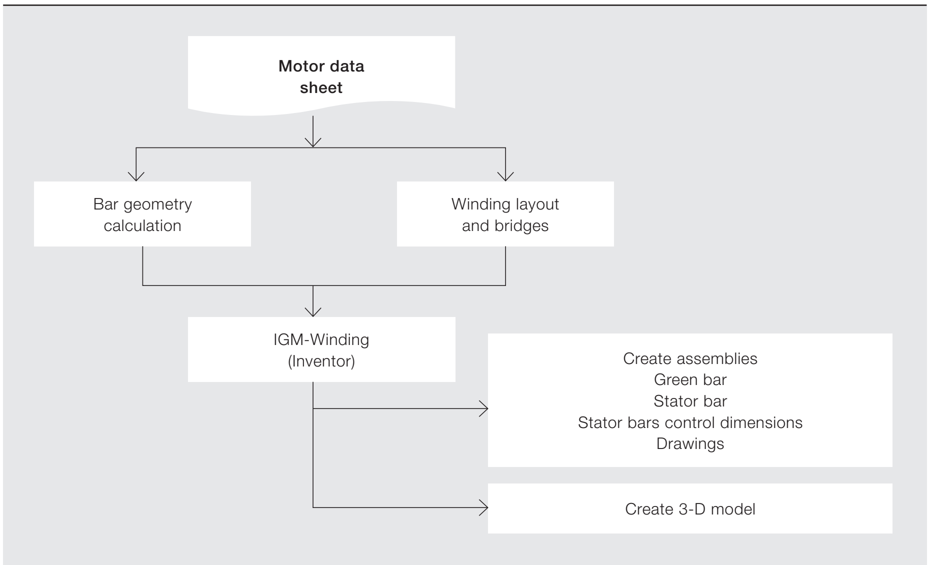


ABB delivered the world's first GMD, an 8,600 horsepower (6.4 MW) motor for a ball mill, to Lafarge Cement in France in 1969. Since then, GMD systems have become larger, more powerful, and are now operating at higher altitudes – even above 4,000 m – where the extreme environmental and boundary conditions challenge the lifetime of a GMD. Under these demanding conditions, only the very best winding design will perform.

Optimal design with IGM-Winding

The current design approach for GMDs is to develop 3-D GMD models based on parameterization and to generate 2-D manufacturing drawings. Today, the parameters are calculated from the motor specification data and a 3-D model is then created automatically. This model is the basis for further detailed engineering and numeric simulations. The most complex part of this is the motor winding design.

Without the proper tools, winding design and optimization is almost impossibly demanding, requiring a huge amount of time just to evaluate possible winding layouts and minimize the risk of winding failures due to insufficient air clearances. The objective, then, was to develop a tool that would create a parametric 3-D model – from the single bar to the complete winding assembly – that allows evaluations and optimizations of different winding layouts before the best option for manufacturing is chosen. The output of the tool is the complete set of optimized and reviewed construction drawings necessary for the winding manufacture, and later, quality control. The tool ABB developed to do this is called IGM-Winding.

The design tool was implemented in three stages: the bar geometry calculation, the winding layout calculations and the 3-D parametric model of the winding.

Three stages, one project

Over the last two years, the design tool has been implemented in three stages, encompassing: the bar geometry calculation, the winding layout calculations and the 3-D parametric model of the winding. The tool output is the construction drawings of each piece required to build the winding → 1.

The bar geometry calculation consists of a short routine that allows the geometrical calculation of the stator bars, using as inputs the values of the motor data sheet.

The winding layouts and bridges are calculated with a tool developed by ABB → 2a. The jumpers can be arranged in different ways without influencing the electrical layout of the design → 2b. When the final layout is chosen, it is necessary to create a list to define which type of bar is located in which slot → 2a.

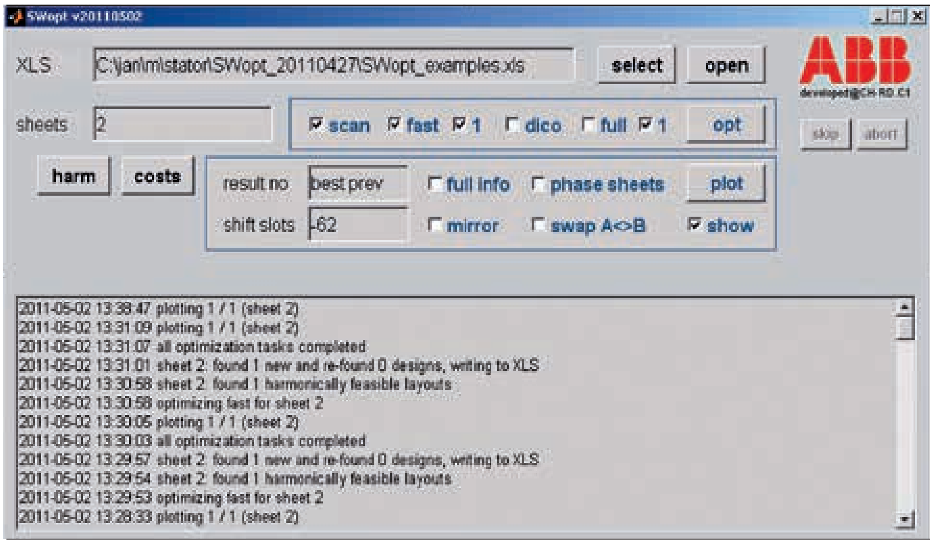
The 3-D winding tool, IGM-Winding, implemented in Autodesk Inventor, builds and draws the 3-D parametric model of the winding and its components, using as inputs the values obtained from the bar calculation geometry and the winding layout calculation.

Choosing the best winding layout

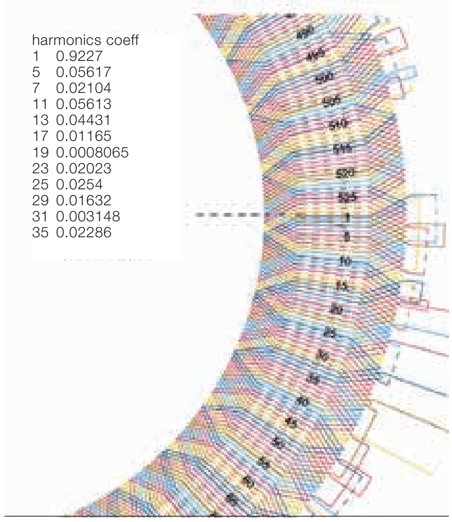
Deciding on the best winding layout is a challenging optimization problem. Since fractional windings (layouts where the

Title picture
ABB's sophisticated IGM-Winding design tool provides electrical machine engineers with a powerful means of optimizing windings. The resultant higher-quality product saves cost, speeds installation and lowers failure risk – especially welcome in remote locations.

2 Winding design tool



2a Typical display



2b Winding layout obtained with the tool

number of slots is not an integer multiple of the number of poles times the number of phases) are typically preferred for their favorable harmonics properties, each coil cannot just be connected directly to a neighboring coil. A valid winding layout must contain jumpers, which bridge gaps between coil ends that are some slots apart. These jumpers may be placed in more or less favorable ways, where the main criterion is the minimization of material (copper) and manufacturing costs. In fact, the layout problem for one single phase is an example of the famous traveling salesperson problem (TSP), which is one of the most widely studied problems in mathematical optimization. The goal is to find a route going through all coils (in TSP terms: cities) exactly once, such that the cost of the route (which is the cost of the connectors) is minimal. The TSP problem is known to belong to a class of problems that are hard to solve at present and it is widely believed that these problems will remain hard in the future.

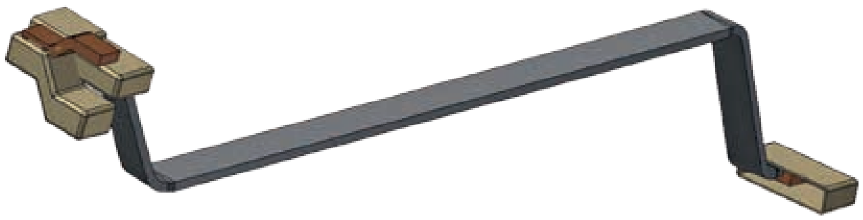
For the winding layout itself, a problem even tougher than the TSP problem has to be solved: There is one TSP problem for each phase and they interact because all the jumpers selected for the optimized layouts must not conflict with each other. Moreover, the electric fields induced around the jumpers interact if the jumpers are adjacent, so favorable interactions of fields that cancel each other out, rather than reinforce each other, are sought. In addition to the placement of the jumpers, the assignment of the bars to the three phases has to be decided and this decision influences the harmonics properties of the winding.

The task of optimizing the winding layout is translated into commonly used mathematical optimization frameworks: mixed integer programming (MIP) and constraint programming (CP). The MIP formulation offers the advantage that (piecewise linearized versions of) all design criteria can be accommodated in the framework. On the downside, MIP solvers typically employ a branch-and-bound strategy over a search tree, which may take large amounts of computational time to complete to proven optimality. CP, on the other hand, is a different approach that executes a search for good winding layouts guided by the constraints of the problem (the geometrical conflicts of the jumpers). It has the advantage that it can often produce very good solutions very quickly, but without the guarantee of global optimality.

3-D winding design

The first step in the 3-D winding design process is the creation of the 3-D winding assembly – a complete stator where the total number of slots is filled with the corresponding top bar (TB) and bottom bar (BB). For this first step, it is necessary to create a 3-D bar assembly that includes the bar plus all associated elements – ie, different lugs, z-connections and insulation caps. This is done for the top and bottom bar, because they are geometrically different → 3.

3 Bottom bar assembly with all elements (lugs, Z-connection and insulation caps)



The biggest innovation of IGM-Winding is its ability to parameterize, in 3-D, any winding layout, thus aiding comparison between variants and facilitating automatic drawing creation.

Once the TB and BB assemblies are built, the tool starts to automatically fill each slot of the 3-D winding assembly with the corresponding TB and BB type. After finishing, the 3-D winding assembly corresponds to a 3-D parametric representation of the winding layout.

Normally, it is possible to obtain several electrical winding layouts with different jumper combinations for one design.

The TSP problem is known to belong to a class of problems that are hard to solve at present and it is widely believed that these problems will remain hard in future.

The biggest innovation of IGM-Winding is the ability to parameterize, in 3-D, any winding layout, thus aiding comparison between variants and allowing the automatic creation of all construction drawings.

Once the winding layout is chosen, the 3-D design process continues with the integration of the winding into the frame ➔ 4. This step is crucial for the validation of the design, especially for GMDs located at high altitudes, and to corroborate by accurate measurement all the distances needed to install or adjust critical elements in the machine.

The layout of the terminal bars is embedded into the frame ➔ 5. This is the only part of the design that is done manually and it takes into consideration the best possible routing – based on bending angles, length of terminal bars and position of the terminal box.

IGM-Winding user interface

The IGM-Winding user interface determines the general software settings. The program generates the protocols of the steps and drawings during the process. These are stored in “Info” and “Log” and can be exported to a CSV file. The function called Green Bar creates two drawings: one for the green bar and one for the consolidated bar. These drawings are required at the beginning of the design process and they are sent to the copper supplier to produce the Roebel bars.

The function “Create Assemblies” needs to be executed before additional drawings are produced. It creates all the 3-D models of the different TB and BB assembly types (M01, M02, etc.) and their different elements.

The functions “Stator Bar” and “Stator Bar Control Dimensions” produce the drawings of the different bar types in a winding layout and their respective control dimensions for bar manufacturing. These drawings are very important for the bending tool manufacturing, for the bar production and for quality control.

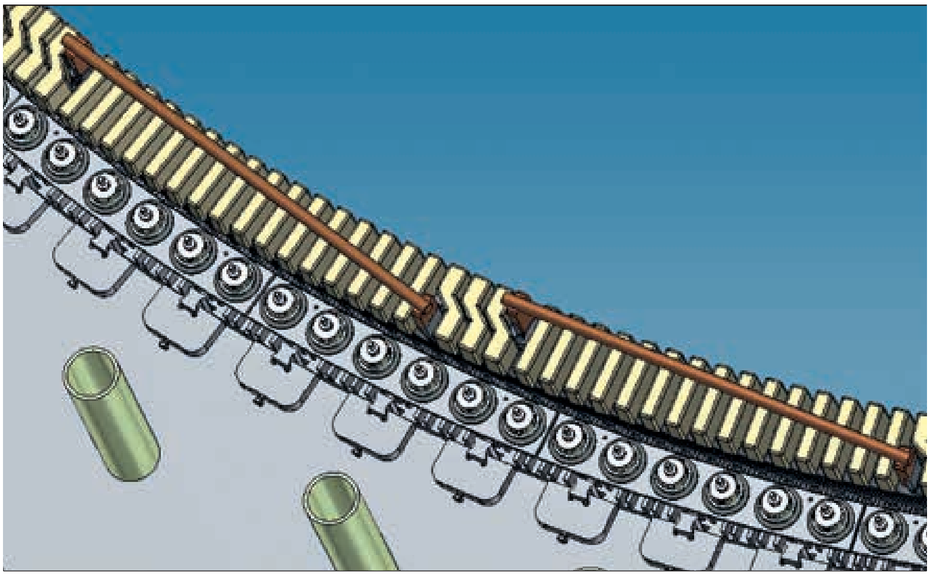
The function “Create 3-D Model” produces the 3-D winding assembly.

Optimization potential

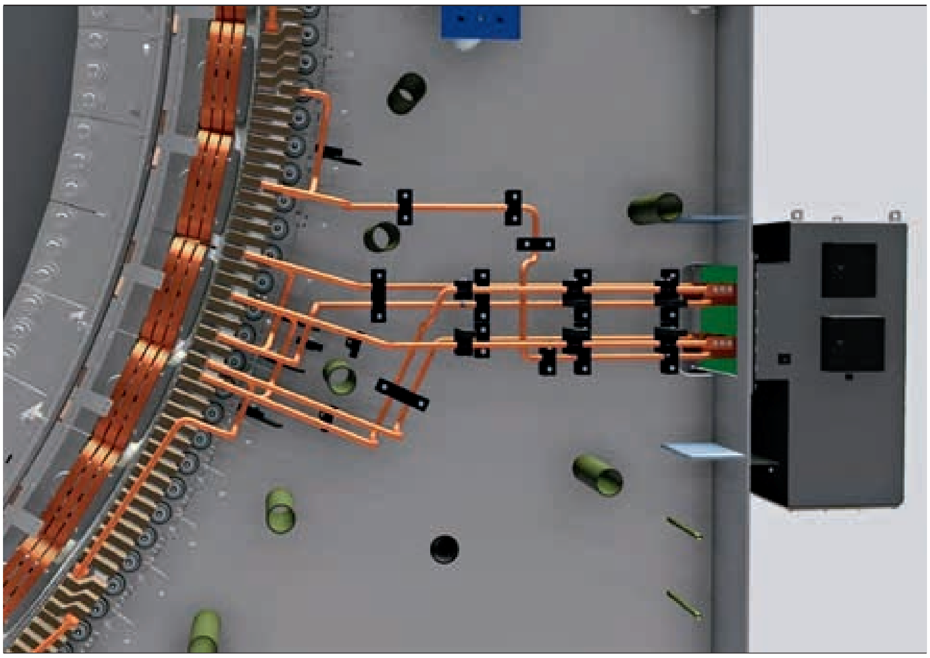
Once all the information is collected and the different possible winding layouts are defined, the optimization can take place.

The task of optimizing the winding layout is translated into commonly used mathematical optimization frameworks.

4 Integration of the winding into the frame



5 Terminal bar and phase bars connected to the terminal box. They must be designed with caution as space is limited.

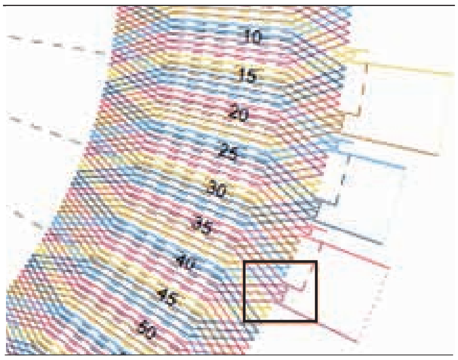


An example of a machine with 540 slots and 36 pole pairs serves to illustrate the capabilities of IGM-Winding.

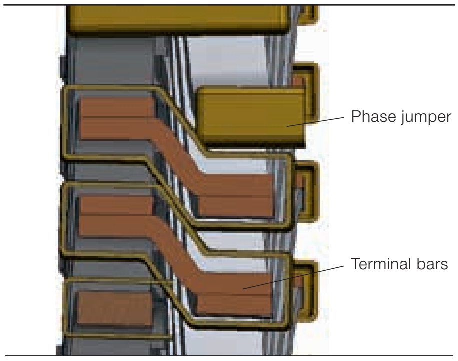
At first sight, the winding layout looks quite simple, with no jumpers in the stator winding, only the phase jumpers in the area of the terminal bars. A detailed view shows the phase jumpers, terminal bars and z-connections → 6. A 3-D winding assembly is marked in the black square, with a top view of the area in → 7. Thanks to the 3-D view it is possible to predict two regions where conflicts will appear when building the insulation caps over the bar connections on the winding. The space between the terminal bar insulation cap and the z-connection next to it does not permit construction. It is the same situation between the phase jumper insulation cap and the neighboring z-connection. Due to a lack of space it is not possible to build this winding using z-connections. For an alternative solution it is necessary to consider the minimum distance between the connections, and the feasibility of construction and insulation of the new connection geometry.

The optimization process can take place at any stage of the design and in this specific case includes mainly the construction feasibility of the alternative piece, preserving the minimum tolerances and air clear-

6 3-D winding assembly layout. The detail of the area in the red square is shown in the next figure.

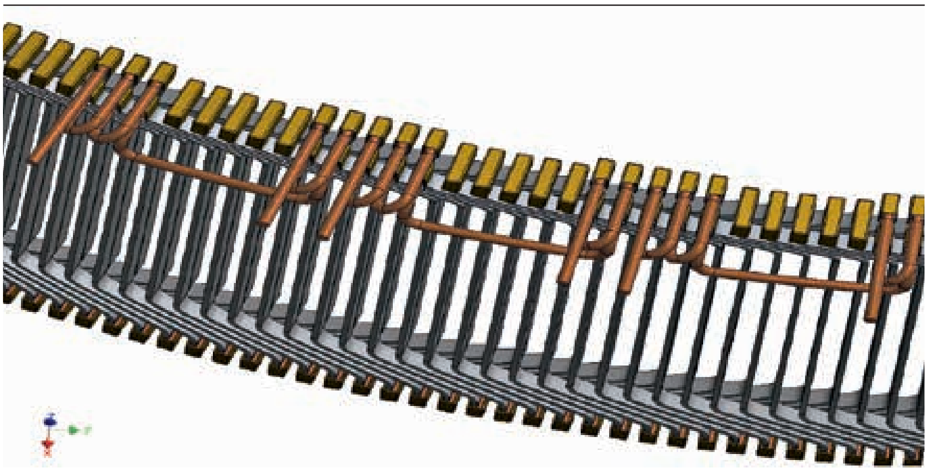


7 3-D view of winding layout



ABB's unique IGM-Winding tool optimizes the winding layout of an electrical machine, helping the design and construction teams to make the best decisions based on accurate, parameterized 3-D models.

8 3-D winding assembly



ances. The 3-D view of a winding layout shows a completely different scenario than the 2-D winding layout → 8.

The cost optimization, without any effect on quality or performance, is not only related to the number of bridges present in a winding layout. It can also be related to the price of a z-connection compared with the price of a small, bent bridge. The cost of the additional inductor required for a z-connection brazing, as well as brazing time, location of terminals, length, etc., disappears when the small bridge is applied (same inductor as terminal bars). All of these aspects should be considered in order to obtain the best feasible solution.

Optimized design, minimized risks

ABB's unique IGM-Winding tool optimizes the winding layout of an electrical machine, helping the design and construction teams to make the best decisions based on accurate, parameterized 3-D models. The automated process and foresight delivered in the early stages of critical design problems allow the minimization of design and drawing creation time.

The accurate prediction of critical distances minimizes the risk of manufacturing problems and, later on, of premature failure of the windings due to poor design, especially for GMDs located at high altitudes. IGM-Winding can be used to design any motor or generator and is already in use for ABB's GMD designs.

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