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Advances
in
Hydrogenerator Refurbishment Technology

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1. Introduction

This paper summarizes several of the latest technological advances in hydrogenerator refurbishment technical analysis over the past 30 years. Very old hydrogenerators around the world are not being retired, but rather are being refurbished, with new turbine runners, new stator windings, reinsulated field coils and other improvements. These enhancements are done not only to prepare the unit for many years of future service, but also to enhance the operation of the unit by increasing power output or improving unit efficiency. In preparation for just such a refurbishment, considerable technical analysis must be done.

Many hydrogenerators can be uprated with power output increases anywhere from 10 to 60%. Typically, the percent of rating increase is proportional to the age of the unit (i.e., the older the unit, the higher the possible uprate). This increase in power output also causes an increase in torque, which in turn causes an increase in operating stresses in the shaft, spider and other rotor components. These components must be analyzed for the increase stresses.

This paper presents the evolution of mechanical analysis techniques, from classical, closed form solutions, through spreadsheet and computer automated techniques that improve efficiency, and finally to finite element analysis. A case history as applied to a hydrogenerator refurbishment is also presented.

Increasing the power output is fundamentally driven by the ability to put less quantity, but equivalently stronger insulation around a coil with increased copper cross sectional area. Also, for any given thickness of insulation, redesigning the machine to run at higher temperatures allows for increased power output. Advances in insulation dielectric strength and temperature endurance have made this possible. Improving the machine's ventilation also can increase the total possible uprate. The ventilation flow distribution and the overall flow velocity can be analyzed for these opportunities. As a second part of this paper, ventilation analysis on hydrogenerators will be discussed, first by using a more conventional method of finite differences, and then using more advanced techniques, such as CFD (computational fluid dynamics). A case history of ventilation analysis is also presented.

Along with the advent of supercomputing power, significant advances have been made in the creation of production drawings used for manufacture of hydrogenerator refurbished components. Through the use of CADD (Computer Automated Design Drawing), a standard wiring diagram of a generator takes only a few hours to produce, whereas when these were done manually, a full week may be required. A review of the progression of drafting technology is presented, from manual techniques, to two dimensional, to three dimensional solid modeling. Several examples, as applied to hydrogenerators, are included.

2. The Evolution of Hydrogenerator Stress Analysis and Mechanical Calculations

Refurbished hydrogenerators with an increase in power output, require a thorough stress analysis to requalify the existing components. The increase in power output causes an increase in torque, which in turn causes an increase in operating stresses in the shaft, spider, keys, keyways, anchor bolts to the foundation and other areas. In years past, these stresses would be calculated using conventional closed form mechanical equations, such as commonly found in Roark[i] or Timoshenko.[ii] Commonly called “hand calculations” done in this manner, a thorough analysis often would take two to three weeks. Calculations were first done using standard math, then with the aid of a slide rule, then by a hand held calculator. Although the speed at which these calculations could be done has improved through the use of the slide rule and calculator, this technique is still very slow compared to what is available today. And although, these closed form, analytical formulas are excellent in evaluating the overall nominal stresses, they require many simplifying assumptions when complicated geometric and stress calculations are involved.

With the development of spreadsheet applications, these same equations were easily programmed into such software programs as Lotus™ or Excel™. Although these programs provide very fast results, they lack the visually recognizable description of the equations. No engineering symbols are used for the equations. Cell references are used, making visualization of the equation very difficult. These programs are acceptable for the individual who has developed the program, and is familiar with how the cells are referenced and the associated underlying equations. For others who use the program, the lack of equations undermine the fundamental learning and engineering intuition associated with a professional analysis.

A further enhancement to analysis by analytic equation is the use of a software program called Mathcad™. This program is as fast and flexible as the spreadsheet solutions, immediately updating as new constants or values are input. The further advantage for engineering analysis is it’s ability to show the appropriate engineering equation and symbols.

Below is an imported section of a hydrogenerator rotor Mathcad™ program that can quickly evaluate the nominal shear stress in the generator rotor shaft due to uprating. If the radius “R” or the torque “T” is changed, the nominal shear stress is automatically changed, just as in a spreadsheet application.

HYDROGENERATOR ROTOR SHAFT STRESSES

Shaft inside radius, in

$R_i := 1.5$

Shaft outside radius, in

$R_o := 9.5$

Shaft polar moment of inertia, in^3

$$J := \pi \cdot \frac{R_o^4 - R_i^4}{2 \cdot R_o}$$

$J = 1.346 \cdot 10^3$

Shear stress, psi :

$$\tau := \frac{T}{J}$$

$\tau = 7.5 \cdot 10^3$

As mentioned above, the analytic method is great for evaluating the nominal stresses in a rotor shaft, for example. For more complicated geometries, and more involved loading applications, finite element analysis (FEA) is more suited. Although more costly and time consuming, FEA provides the accuracy at the level of detail required for complicated solutions.

FEA in and of itself has advanced significantly over the past 20 years. The first applications were owned only by large corporations, running on huge mainframe computers. The FEA mesh of the component was complicated to build, requiring considerable time and forethought. Currently, advanced FEA applications can be run on high end PC's (personal computers), with automatic meshing. The first applications typically involved simple static stress analysis, but with today's computing power, real time dynamic simulation is now possible.

FEA was employed by National Electric Coil (NEC) during a multi-unit refurbishment project in the northeast United States. These early vintage hydrogenerators were uprated approximately 50% by redesigning the stator coils, using less but stronger grades of insulation in the stator slots. As part of the uprate analysis, a close look at the increased mechanical stresses was necessary. The rotor spider steel was suspect, due to the age of the machine (approximately 68 years old). During inspection of the rotor spiders in NEC's factory, a significant number of large cracks were found in the transition area between the rotor hub and the spider arm. A diagram of the locations of these cracks is shown in **Figure 1.**

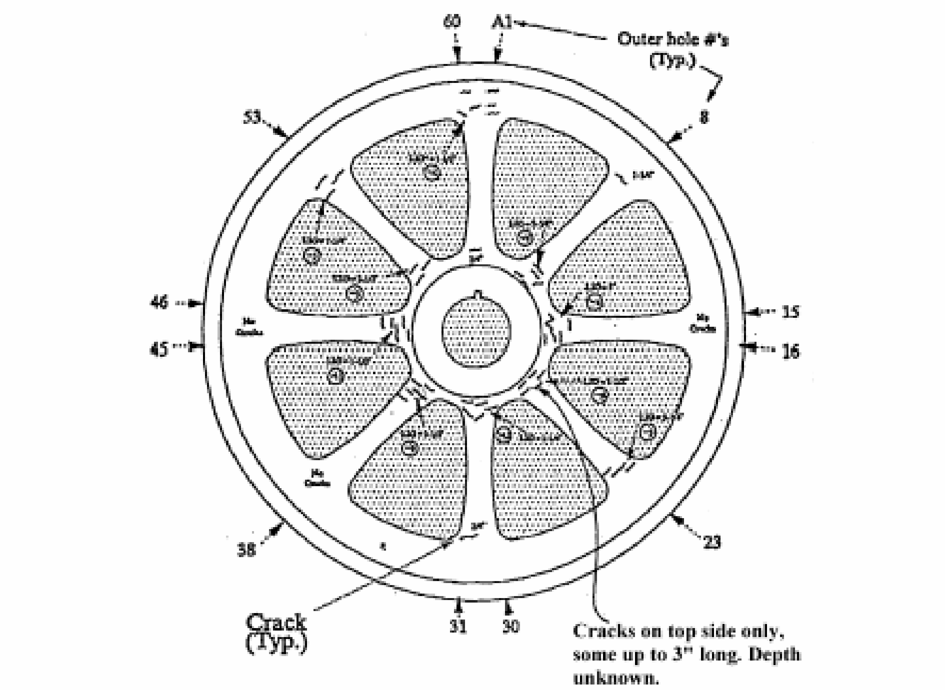

Figure 1. Shown above is an overall sketch of the spider arm and crack locations. Over 50 cracks in various lengths and depths were present on this machine. After this sketch was made, cracks were confirmed on both sides of the spider.

A typical crack, approximately 1.5 inches long, and 0.625 inches deep, is shown in **Figure 2.**

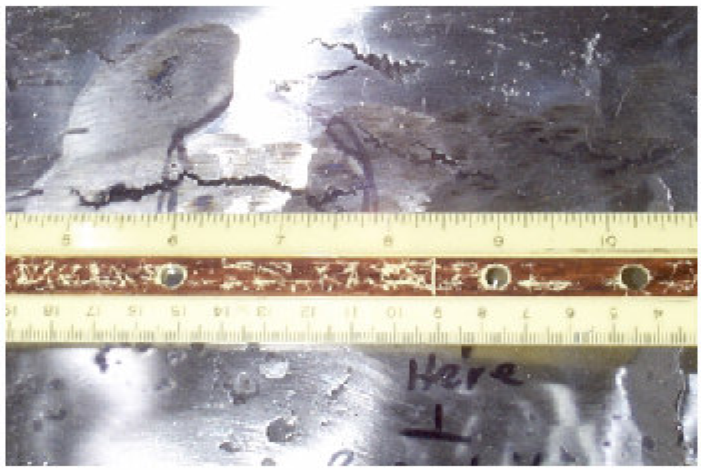

Figure 2. Photograph of cracks in a typical spider arm. Most of the cracks were located at the transition area between the thick hub and the thinner spider arm.

A detailed FEA was done on the rotor spider geometry to determine if past operating stresses could have caused these cracks. A detailed two-dimensional model was made to model the stresses and deflections in one spider arm. The appropriate boundary conditions were added at the rotor hub, and the applicable loadings were imposed; such as that due to rotation, the vertical weight of the arm itself and the pole pieces, thermal growth, and magnetic forces. A plot of the actual stresses and magnified deflection of the rotor arm is shown in **Figure 3**.

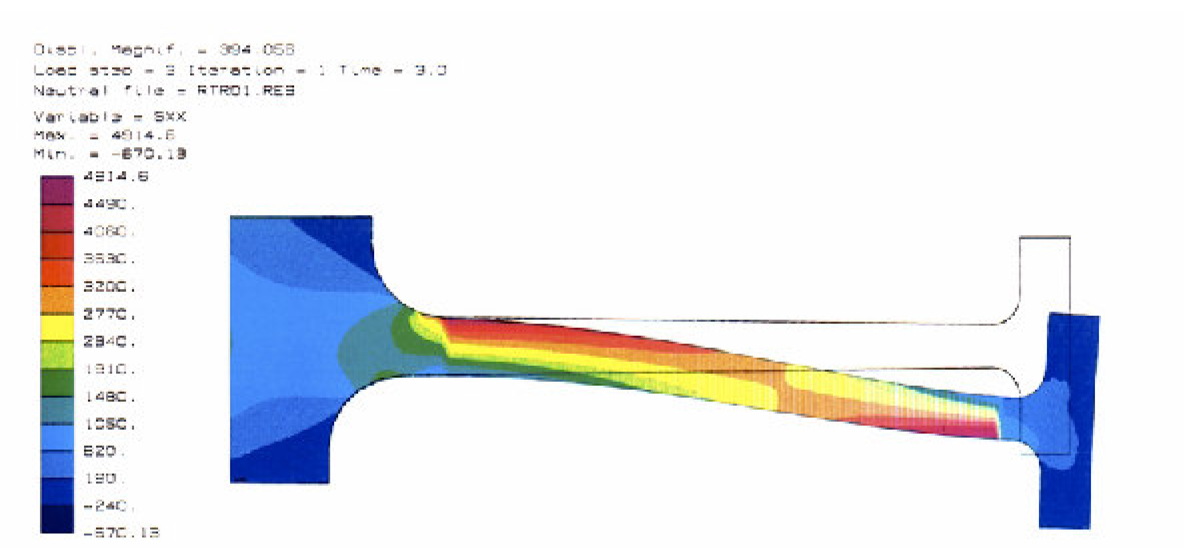

Figure 3. Spider arm stress and deflection at overspeed.

The FEA calculations showed that the existing operating parameters could not have generated the "as-found" cracks in the rotor spider.

The next step was then to use the FEA results, combined with fracture mechanics analysis, to determine if the unit could be operated with these cracks at the new, uprated higher torques. Actual material properties of the rotor spider were obtained to provide a more accurate analysis. Fracture toughness values were obtained by a material sample taken by a trepan specimen through one of the larger cracks. This specimen also provided the opportunity to closely examine the crack surface metallurgy with a SEM (Scanning Electron Microscope). The combined FEA and fracture mechanics analysis showed that all cracks deeper than 0.4 inches had to be repaired. The unit could not run at the uprated values with the existing cracks.

At this time, options for new spiders were evaluated. Quotes for new spiders, either from fabricated steel structure, or new casting, came in at about double the estimated cost of the repair. More of a concern, however, was the long lead time for a new spider, on the order of 6 to 10 weeks. It was estimated that the repair could be done in 2 to 3 weeks. Since this customer was in need of these units for generation, and because of the higher costs for a new unit, a decision was made to repair the spiders at the NEC factory.

The large concentrated area of cracks in the web areas were ground out into large "V" shaped cavities to make suitable for weld repair. All grinding, welding and heat treating was done in National Electric Coil's factory in Columbus, Ohio. After all grinding was completed and all cracks removed and verified by magnetic particle exam and dye penetrant test, the entire spider was pre-heated for welding preparation as shown in **Figure 4.**

Figure 4. Setup of spider for pre-heat and post-weld heat treatment.

Uniform pre-heating was necessary to prevent distortion. After all welding was completed, the unit went though a post-weld heat treatment cycle. It was then allowed to cool to room temperature. Final assembly and balance of the spider wheel assembly with the pole pieces on was accomplished in National Electric Coil's balance pit as shown in **Figure 5.** All units have been operating without incident for the last two years.

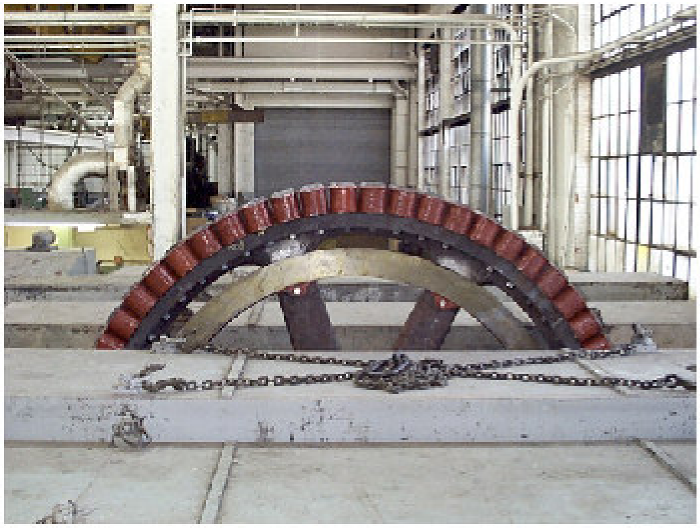

Figure 5. Photograph of spider in National Electric Coil's balance pit. Pole pieces, as shown, are assembled on the spider.

3. Improvement in Ventilation Analysis as Applied to Hydrogenerator Refurbishment

Increasing hydrogenerator ventilation can be important during a refurbishment project since it can provide a significant additional increase in generator power output. This increase is above and beyond the increase obtained by changing the stator coil design and increasing the copper cross sectional area of the coil. Increasing the air flow through the machine to improve ventilation is not an exact science, however, since so many variables are involved. For instance, small changes in geometry, which can affect entrance and exit losses, can significantly affect the ventilation.

Before a ventilation analysis can be done, the existing air flow through the machine must be well understood. If access to the machine is available, air velocity through the stator core vent ducts can be measured with a pitot tube. It is important to measure every vent duct along the length of the core to get a good flow distribution for the machine. In many cases, the flow from top to bottom can have significant imbalances due to the rotor geometry, baffle location, differences in fan design from top to bottom, or plugging of the vent ducts. An anemometer can be used over the cooler openings to determine the air flow through the coolers. This actual air flow data can be used in conjunction with past heat run data to develop a thermal model of the stator winding. This thermal model will calculate the temperature rise in the stator coils for a given power output.

If the unit is unavailable for direct measurement of airflow and vent velocities, past heat run test data can be used to develop a reliable thermal model, and then back calculated to find the expected air flow. Then, using this calibrated thermal model, estimates of increased power output can be made on estimates of increased ventilation.

There are currently two techniques the author's company uses for ventilation improvement analysis. The first involves simultaneous equations set up as an electrical resistance network. This more conventional method of ventilation flow analysis is accurate, less costly and significantly faster. The second technique uses Computational Fluid Dynamics (CFD). This method can be more accurate in localized areas, and can handle more complicated geometries. The trade off, however, is that this method is much more costly and time consuming.

Examples of both types of ventilation analysis were used in a large, multi-unit hydrogenerator contract awarded to NEC by the Army Corps of Engineers (COE). The project involved uprate of four machines from an original rating of 73 MVA to 95 MVA. The first type of ventilation analysis used an electrical network model, as shown in **Figure 6**.

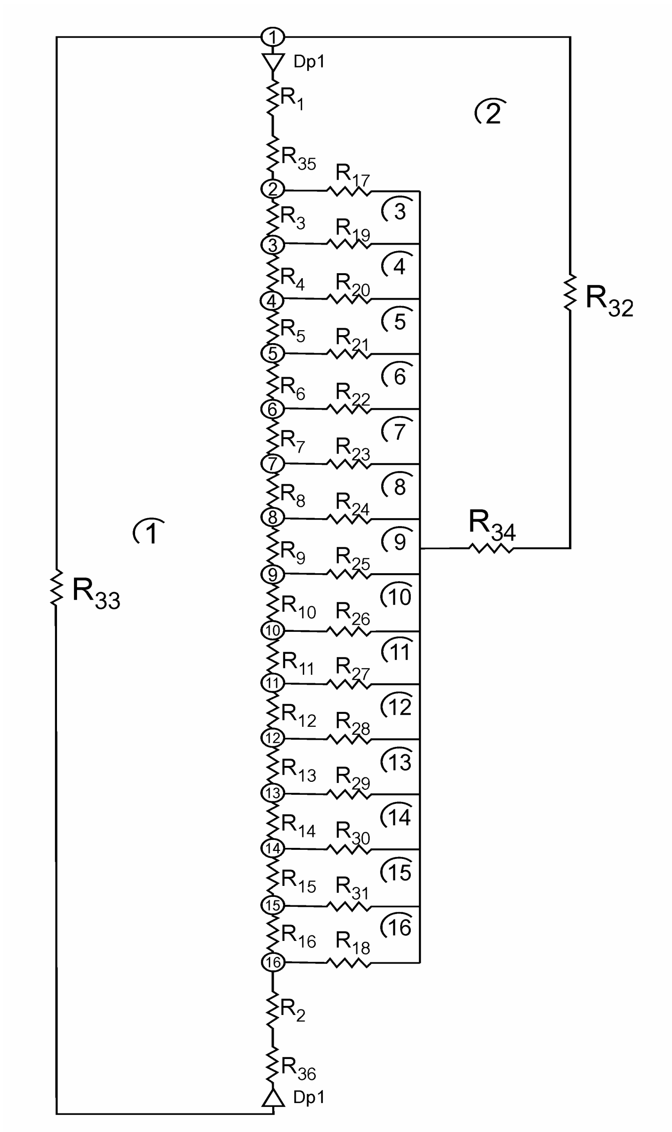

Figure 6. Resistance element network for hydrogenerator ventilation analysis.

Resistances in series and parallel were used to simulate series and parallel ventilation flow paths through the generator. These units have a combination of air flow through the rotor rim vents, and around both the top and bottom end turns. A detailed ventilation analysis was performed on the common design for each machine. An anemometer was used to measure total air flow at the coolers. Vent velocities were measured at the back of the stator core with a pitot tube. Access panels had to be removed to allow access to the vents. The flow distribution from top to bottom showed that the air flow is lower on the top one third of the machine.

With the air flow unbalanced, hot spots in the stator winding could develop in regions of lower flow. The present ventilation system was modeled and calculated to show a flow of 123,000 cfm. The calibrated thermal model, as determined from past heat run data, showed that a stator coil temperature rise of 75.8 degrees C., results from this level of air flow in the machine.

The goal of the refurbishment project was to uprate the machine 30% to 95 MVA, but limit the stator coil temperature to 70 degrees C. The calibrated thermal model showed that this would require an air flow of about 150,000 cfm in the machine. Another goal, in addition to the increased rating and air flow, was to better distribute the air flow in a more uniform pattern.

Several design iterations were tried to improve the machine ventilation flow to the required cfm. Modifications that improved the air flow most significantly were design changes in the fan blades. The existing fan blades were changed to a much more efficient backward curved design. The inside diameter of the blades was also decreased to increase the associated pressure drop. The inside diameter of the bottom blades was decreased by four inches. The inside diameter of the top blades was decreased by two inches. These changes brought the calculated air flow up to a maximum obtainable value of 147,000 cfm, resulting in an associated stator coil temperature rise of 70.7 degrees C. NEC considered this design to be acceptable and provided enough of a safety margin so that all guarantees could be met.

A more sophisticated method of analyzing air flow is by the use of CFD (Computational Fluid Dynamics). Both the fluid and solid areas of the hydrogenerator were modeled using Star-CD™. Star-CD™ is a multi purpose CFD computer code, with the ability to determine velocities and flows in complex structure. The calculation methodology is finite-volume based, allowing the model to be unstructured and boundary fitted.[iii] This computer code iterates on a set of non-linear equations based on the governing set of equations for continuum fluid flow. The final flow solution is fully three dimensional, steady, incompressible, viscous and turbulent.

NEC used CFD as a double check on the ventilation analysis and corresponding thermal model. Unlike the resistance network calculation method, the CFD model incorporates separate solid and fluid domains. The fluid domain consists of the air passages throughout the machine, including the air gap, vent ducts in the stator core, radial vents through the rotor rim, and circulatory paths around the winding end turns. The solid domain consists of the rotor, field coils, stator core and windings, coolers and support structure. The assembled computational mesh represents 1/6 of the total flow domain through and around the machine. The sector model is used in the analysis with cyclic boundary conditions applied at radial surfaces located sixty degrees apart.

The CFD model used for this ventilation improvement analysis contains over 2.8 million cells or elements. Approximately 1 million cells are located in the stator vents, while another 1.2 million cells surround the rotor poles, brakes and fan blades. The remaining 0.6 million cells take into account the remainder of the unit.

With the use of this CFD technique, new and improved methods of ventilating the unit with increased air flow were also analyzed. A section of the three-dimensional model used in the analysis is shown in **Figure 7**. A dynamic model showing the actual flow of air through the machine was also created. **Figure 8** shows a cross section of this model. Although CFD provides increased accuracy in the ventilation analysis, for most proposals, it is too time consuming and costly. After the award of the job, it may be more cost effective, depending upon the needed uprate percentage. Although initial results from the CFD model substantiated results from the resistance network model, continued analysis by CFD took too long to obtain

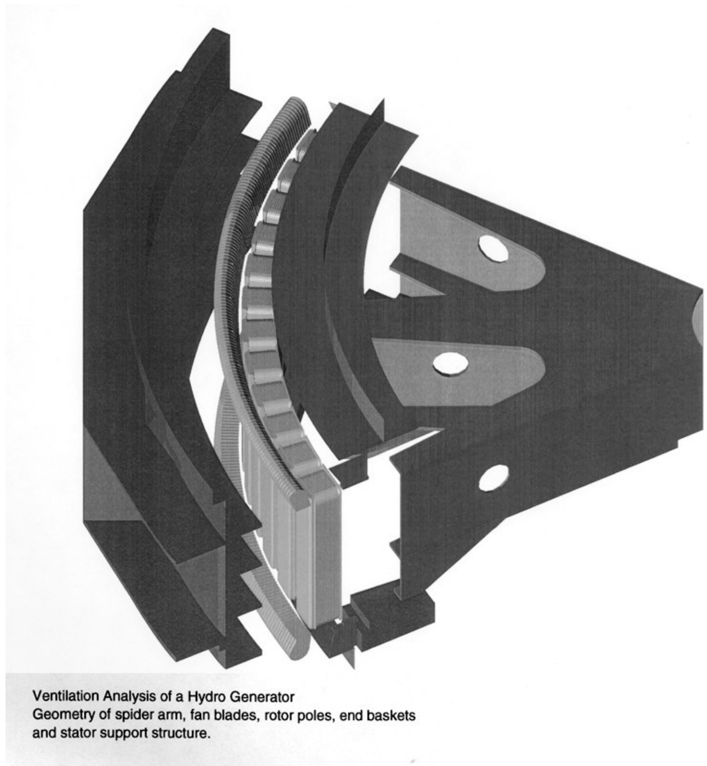

Figure 7. CFD (Computational Fluid Dynamic) model of a hydrogenerator to analyze ventilation. Shown in this particular model is the spider arm, fan blades, rotor poles, stator end winding coils and the stator support structure.

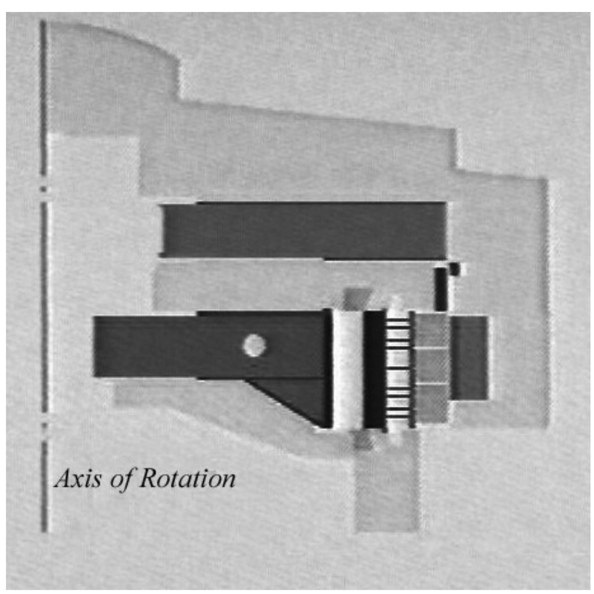

Figure 8. Screen capture photograph of the CFD dynamic model, simulating in real time, air flow through the generator.

Although CFD provides increased accuracy in the ventilation analysis, for most proposals, it is too time consuming and costly. After the award of the job, it may be more cost effective, depending upon the needed uprate percentage. Although initial results from the CFD model substantiated results from the resistance network model, continued analysis by CFD took too long to obtain additional definitive answers. Based on initial agreement with the resistance network model, design improvements were initiated based on the results from the resistance network model. Although in this instance, CFD proved cost prohibitive time consuming, as computing power continues too increase, there is no doubt CFD has a bright and continued future in the industry.

4. Advances in Hydrogenerator CADD Technology

The final technology advancement to be discussed is in the area of MDA (Mechanical Design Automation) or CADD (Computer-Aided Design Drafting). Computers have significantly advanced the ability to advance design, manufacturing and other engineering processes, increasing efficiency, accuracy, and capability. According to a recent informal survey of the readers of ASME's "Mechanical Engineering" magazine, CADD was voted as one of the top ten engineering achievements of the 20th century.[iv] Drawings, which communicate engineer's concepts and ideas, are essential for any manufacturer. They minimize ambiguity, and provide a clear picture of the what is to be made. The technology involved in the creation of these drawings has changed significantly over the last thirty years.

With the advent of the computer, manual drafting slowly evolved into two dimensional CADD (Computer Aided Design Drafting) in the late 1970's and early 1980's. Two dimensional CADD then evolved into three dimensions, as engineering workstations moved off of the big mainframes to the powerful and portable PC's. The latest CADD programs incorporate solid modeling, with automatic production of the two dimensional production drawings.

A manually drawn winding diagram, made in the early 1970's, would generally take two to three days to produce by a layout draftsman. Today, as shown below in **Figure 9**, an automatically produced computer generator winding diagram can be made in just a few hours.

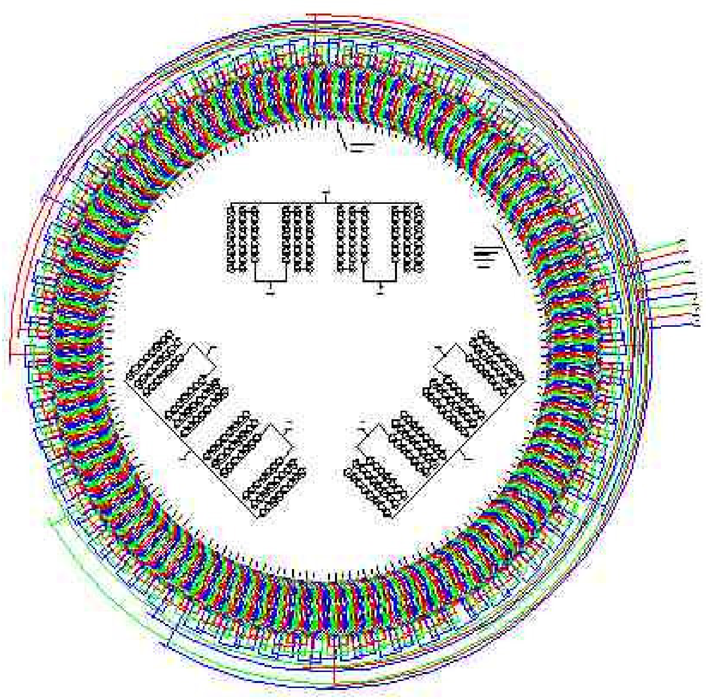

Figure 9. Computer generated winding diagram for a hydrogenerator.

As we begin the 21st century, it is estimated that more than one million engineers and designers worldwide are using advanced three dimensional solid modeling technology, and probably another two million use two dimensional mechanical drafting. In the time span of about twenty years, we have gone from manual layout drafting and simple two-dimensional computer aided drafting workstations costing $125,000 per seat, to $7,000 PC (Personal Computer) based systems using advanced three-dimensional solid modeling techniques.

References

[i] "Formulas for Stress and Strain," Raymond J. Roark and Warren C. Young, McGraw-Hill, 1975.
[ii] "Strength of Materials: Part I and II," S. Timoshenko, Robert E. Krieger Publishing Co., 1984.
[iii] Evaluating 43-Inch Generator Rotor Thermal Behavior Using Computational Fluid Dynamics (CFD) Techniques," L. Shuster, et. al., International Joint Power Generation Conference, ASME.
[iv] "Mechanical Engineering's Top Achievements of the 20th Century," Mechanical Engineering Magazine, April 2000, pp. 52-59.

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