Bolt Tightening Control Method for 4P Generator with Solid-Pole Rotor

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Abstract

For a 4P generator with a solid-pole rotor, a large load is applied during operation to the bolts that clamp the pole shoes, which support the field coils on outer diameter side of the magnetic poles. On the other hand, in order to suppress the repeated loads, it is necessary to increase the axial force (fastening force), thus the constraints on the permissible range of fastening force is severe. We have, therefore, developed a bolt tightening control method that can manage fastening force with high accuracy so that it can satisfy the constraints.

In the case of the torque control method that is a generally adopted as bolt tightening control method, the instruction torque value is determined to meet the constraints on the axial force which is estimated based on the tightening torque. Accuracy level for axial force estimation is, however, very low. Where the level of constraints is very high, it is impossible to adopt this method. In case of our newly developed bolt tightening control method, the axial force can be directly measured so control is possible even when the constraints are severe. In addition, in order to improve the productivity of assembly, we improved the tightening control method by using an elastic rotation angle tightening.

1 Preface

Compared with salient pole generators with a laminated rotor core, the 4P generator with a solid-pole rotor has a high rated speed. In addition, the rotor diameter is large and mass of field coils are large. Therefore, the centrifugal force applied to the field coils becomes larger. Since the field coils are supported by the pole shoes mounted on the outer diameter side of the magnetic poles, a great amount of axial tensile load (axial force) is added to the bolts that are used to clamp the pole shoes to the magnetic poles during operation. While, in order to suppress the repeated loads and prevent the bolts from loosening, it is indispensable to secure a high tightening force. From these requirements, constraints on the permissible range of pole shoe bolt tightening force becomes severe for both upper and lower limits. In the case of conventional bolt tightening control method like torque control method where tightening forces may vary significantly, it is impossible to satisfy the permissible range. Accordingly, for the tightening of pole shoe bolts, an improved bolt tightening control method is required so that the bolt tightening force can be controlled with high accuracy. This paper introduces our bolt tightening control method developed through tests to specify various factors that affect the characteristics of bolted joints.

2 Elastic Axial Force Control Method

In order to control tightening force with high accuracy, we developed a bolt tightening control method ("elastic axial force control method" hereafter). Under this method, the axial force itself is directly controlled as the control item while the torque tightening is used for the bolt tightening method. The control standard values, control methods as well as the tests and verifications that provide the basis for them are described below.

2.1 Standard Values of the Elastic Axial Force Control Method

Fig. 1 shows a bolt tightening control diagram. For the elastic axial force control method, three types of standard values are used: (1) the lower limit to suppress the repeated loads during operation,

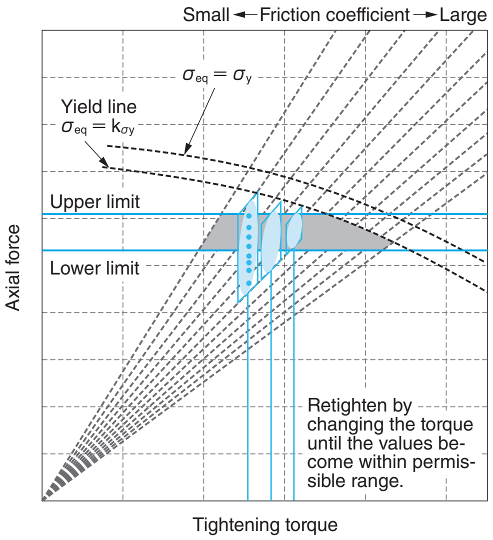

Fig. 1 Bolt Tightening Control Diagram

The upper limit, the lower limit, and the yield line are shown. The yield line used for control is lowered with margin from the line where the equivalent stress (σ_{eq}) reaches the yield strength (σ_y).

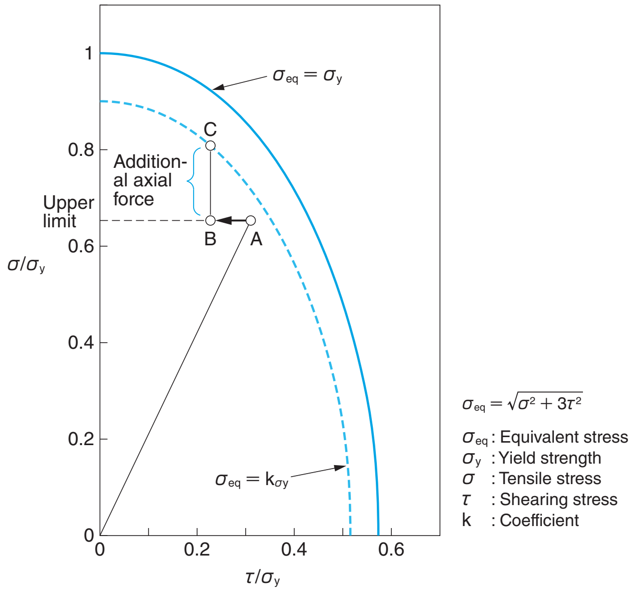

Fig. 2 Relationship between Equivalent Stress, Upper Limit, and Additional Axial Force

In the process of bolt tightening where tensile stress and torsional force are superposed, it yields when the equivalent stress (σ_{eq}) as shown above equation reaches the yield strength (σ_y). The dotted line shows the yield line defined considering measurement error. Assuming that the added axial force during operation is B-C and lost shank torque immediately after tightening is A-B, Position A falls on the upper limit.

(2) the yield line to avoid exceeding of static strength during bolt tightening, and (3) the upper limit to avoid the exceeding of static strength during operation.

(1) Lower limit

Many pole shoe bolts are allocated on the pole shoes. The stress analysis by the Finite Element Method (FEM) was repeatedly performed to realize an arrangement that reduces the repeated loads applied to the bolts as much as possible, and the minimum fastening force that satisfies the conditions was obtained. A value considering an axial force measurement error is set as the lower limit for the fastening force. The lower limit during initial tightening, however, is raised considering the initial loosening described later. With this consideration, the need for retightening is reduced.

(2) Yield line

Fig. 2 shows the relationship between equivalent stress, upper limit, and additional axial force. Alloy steel bolts are used for pole shoe bolts. The bolts to be torque-tightened are superposed with tensile stress due to axial force and shear stress due to shank torque. In this case, since the steel material yields according to the equivalent stress, the equivalent stress should not exceed the minimum value of the bolt strength, and the line taking into account the measurement error of the axial force and torque is used as the standard. Since the shank torque cannot be measured directly with the actual machine, we use the estimated value from the tightening torque.

(3) Upper limit

The upper limit is the fastening force value at which the equivalent stress does not exceed the yield line even if additional axial force due to the centrifugal force of the coil is added during operation. Since the shank torque is reduced immediately after the completion of tightening, the upper limit is determined in consideration thereof. This process is indicated by the arrows in Fig. 2.

2.2 Axial Force Control to Reduce Axial Force Variation

In the torque control method, the fastening force is statistically estimated from tightening torque and friction coefficient and their variation. The variation of the estimated values is very large. The fastening force cannot, therefore, be managed to be within a narrow permissible range. In the elastic axial force control method, the axial force is then directly managed by measuring the axial force of each pole shoe bolt by using ultrasonic bolt load meter. As a result, the manageable range can be narrowed to the measurement error range of the bolt load meter. Fig. 3 shows an ultrasonic bolt load meter. When selecting a bolt load meter, we consid-

Fig. 3 **Ultrasonic Bolt Load Meter**

This shows a scene of measuring initial bolt length with an ultrasonic bolt load meter. In order to reduce transducer placement error, a positioning jig for each type of bolt is produced and used.

ered not only the measurement accuracy, but also the sensor installation position and processing restrictions on product bolts. **Fig. 4** shows a comparison between the elastic axial force control method and the torque control method.

2.3 Influencing Factors of Elastic Axial Force Control Method and Verification Tests

In order to obtain adequate standard values for the elastic axial force control method, we conducted verification tests on various factors that influence the standard values.

2.3.1 Principle of Bolt Load Meter and Calibration Test

The bolt load meter used is a type of ultrasonic bolt tension meter which measure the propagation time in the bolt axis direction. Using the bolt so that the bottom of the hexagon socket and the screw tip are in a plane perpendicular to the axis, a pulse wave is emitted from the head side where the transducer of the piezoelectric element is attached, the echo from the screw tip is received, and the propagation time is measured. By specifying the propagation speed according to the material, the elongation can be measured by calculating the difference between the length measured in advance without the load and the time length when tightening is done. Also, the axial force can be measured from the elongation by conducting a tensile test with the same grip length of the actual machine and obtaining the relationship between the load and the elongation. Though the ultrasonic wave propagation speed depends on temperature and stress, during this load-elongation calibration test, calibration can be performed including the effect of stress. The effect of temperature was tested using a constant

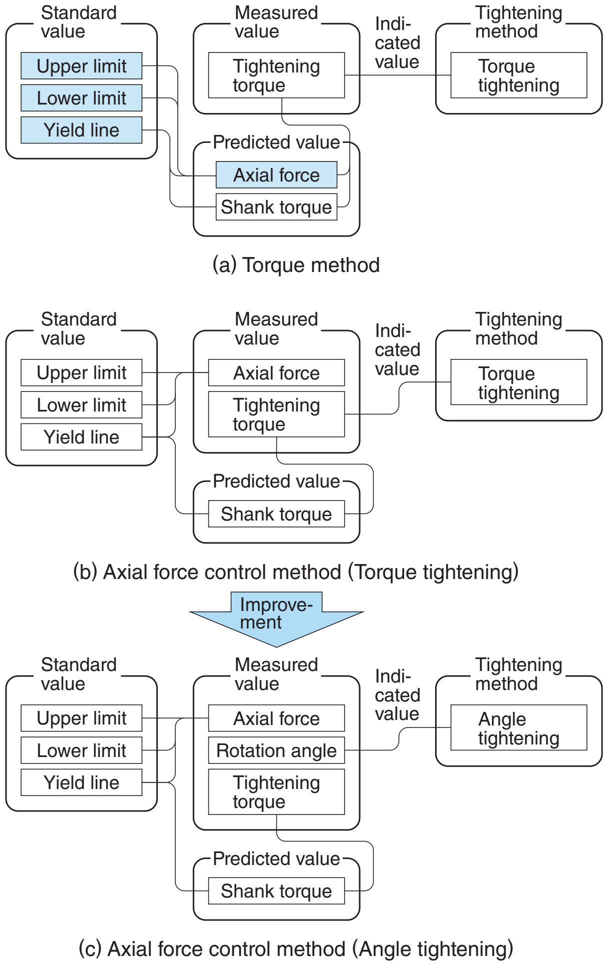

Fig. 4 **Comparison between Elastic Axial Force Control Method and Torque Control Method**

Comparison is shown between our elastic axial force control method and the torque control method. In the case of the torque control method that is generally used, it is impossible to narrow the standard value range because an estimated value with low accuracy is used for the axial force.

temperature test chamber, and the validity of the coefficient was confirmed.

2.3.2 Fatigue Strength

Regarding the fatigue strength data for large diameter bolts, there are almost no reference documents nor reference cases. A standard by the Association of German Engineers, VDI 2230 Blatt 1 (2003), defines a equation that uses the nominal diameter (and mean stress in the case of a bolt with rolling after heat treatment) as a parameter, but the detailed basis is not clearly stated and it is only described as a "guideline."(1) We, therefore, conducted fatigue tests using actual bolts of all sizes (M36 to M64) that we plan to use, and confirmed the effects of mean stress and nominal diameter. **Fig. 5** shows the VDI standard 2230 Blatt 1 (2003) reference values for fatigue strength of high strength bolts, and **Fig. 6** shows an appearance of the bolt fatigue test.

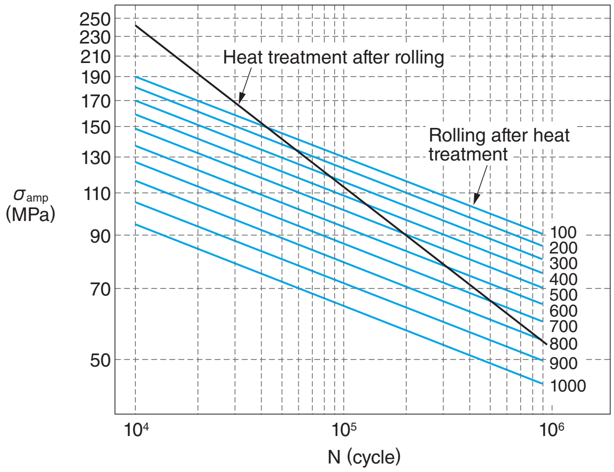

Fig. 5 **VDI Standard 2230 Blatt 1 (2003) Reference Values for Fatigue Strength of High Strength Bolts**

The SN diagram of the high strength bolt is shown. Bolts manufactured by rolling after heat treatment are said to be affected by mean stress. The value at the right end of each line is the mean stress value. It also depends on static strength and bolt diameter. This figure is an example of M36 bolt of property class 10.9.

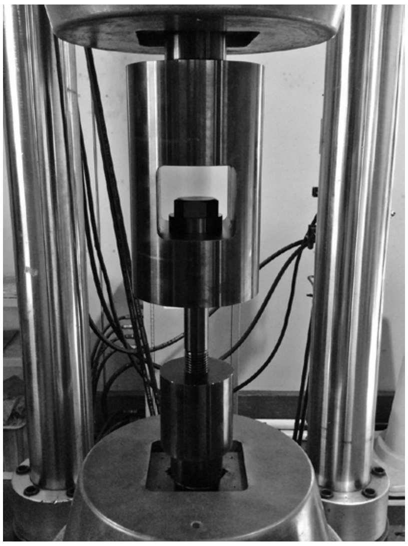

Fig. 6 **Bolt Fatigue Test**

Fatigue test was carried out using real bolts.

2.3.3 Additional Axial Force during Operation

In order to confirm the validity of the stress value during operation obtained by FEM analysis, we measured the strain generated in pole shoe bolts while the rotor was revolving. This was done by using the prototype model. In doing so, we confirmed that the accuracy of analysis was sufficient.

2.3.4 Loosening

The 4P generator with a solid pole rotor is assumed by design that it will be driven by a turbine with low fluctuation torque. For this reason, the loads applied to the pole shoe bolts can be considered as only the axial force to be applied during operation. In this case, the rotating type loosening will take place unless an external force applied is almost equivalent to the fastening force. In addition, FEM analysis and test results on the development prototype machine confirmed that there was no loosening caused by heat and no loosening caused by heat or macro plastic deformation on bearing surface.

We, therefore, decided to intensively examine the loosening that occurs when the contact pressure depresses the surface roughness and waviness of the contact surfaces caused by machining. This examination includes tests to measure the bolted joints for a long duration of time until the axial force change settled down. It also includes tests repeating start and stop operations by using the development prototype machine, and measures the transition of axial forces of all bolts.

2.3.5 Frictional Coefficient

In the torque tightening, the fastening force is strongly influenced by the friction coefficient. When actually fastening, it is necessary to check the friction coefficient. In the elastic axial force control method, the friction coefficient is also used when estimating the shank torque from the fastening torque. Although the friction coefficient varies to some extent, if the ratio between the bearing surface friction coefficient and the thread friction coefficient is fixed, the sensitivity in estimating the shank torque is not as high.

2.4 How to Obtain the Indication Value when Tightening

Although torque tightening was adopted at the beginning of development as bolt tightening method, in order to improve the productivity of assembly, it was changed to the angle tightening.

(1) Torque Tightening

Temporary tightening is performed at a low torque well below the permissible axial force range. Then we confirm friction coefficient range from the temporary tightening result and determine the indication torque value for regular tightening not to exceed yield line. The bolt axial forces are then measured. For bolts whose axial force deviate from the upper and lower limit, new indication torque value is determined and retightening is performed. This procedure is repeated until the fastening force of all bolts are within the permissible range. In the procedure, any bolt exceeds yield line is replaced

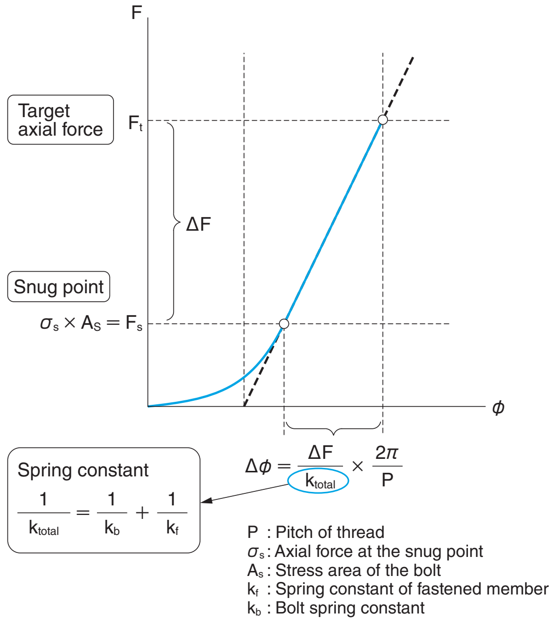

Fig. 7 Concept of Elastic Rotation Angle Tightening

Beyond the snug point where the state of contact on the bearing surface is stable and the relationship becomes linear between the rotation angle (ϕ) and the axial force (F), the rotation angle is determined by the series spring system that is the synthesis of the bolt spring constant (K_b) and the spring constant of the fastened member (K_f).

with a new one.

(2) Angle Tightening

In the torque tightening, the indication torque value is determined based on the friction coefficient at the previous tightening. However, the friction coefficient may change even when the same bolt is retightened. So there was the case where the number of retightenings increased or the yield line was exceeded and the work efficiency was deteriorated. We, therefore, decided to switch the method into angle tightening whose method is less affected by the friction coefficient. In the angle tightening, the relationship between the rotation angle of the bolt and the axial force is obtained in advance, and tightening is performed using the angle as an instruction value within a range in which the rotation angle and the axial force are proportional.

Fig. 7 shows the concept of the elastic rotation angle tightening. Relation between rotation angle and axial force is nonlinear at the beginning of tightening, but it becomes almost liner from the point when some extent of axial force is generated after the bearing surface is seated.

This point is called the snug point. Until this point, it is common to tighten the bolts by specifying the torque. If the influence of the initial non-linearity is large, as a result, the variation rate of the fastening force due to torque tightening increases. The initial non-linearity is caused by the effect of the contact surface stiffness of the contact surface. Since the machining accuracy of the bearing surface is controlled, the non-linearity is almost complete within the range of small axial force. The productivity of assembly has, therefore, been improved by setting the snug point at the small value and reducing the variation in fastening force.

Table 1 Influencing Factors and Verification Tests on Plastic Angle Control Method

The table below shows various factors that affect the plastic control method and verification tests that are currently carried out or being planned in order to confirm the influence.

Factor type	Influencing factor	Test
During bolt tightening	Snug point	Snug point verification test
	Spring constant	Measurement of bolt spring constant Measurement of synthetic spring constant
	Bolt proof strength	Proof strength verification test
	Frictional coefficient	Plastic tightening test
After bolt tightening	Relaxation at room temperature	Room temperature relaxation test
	Loosening under external load	Repeated start-stop tests
	Allowance of additional axial force during operation	External force acceptance test
	Fatigue strength of plastic tightened bolted joint	Fatigue test

3 Postscript

This paper introduced our bolt tightening control methods for a 4P solid pole generator. Currently, we are working on developing a plastic angle control method that can reduce the bolt axial force variation and repeated loads in further level. **Table 1** shows the influencing factors and verification tests on plastic angle control method. We are proceeding the validation tests on inherent influencing factors of the plastic angle control method. In doing so, we expect it will lead to further quality improvement.

《Reference》

(1) The Association of German Engineers: "VDI 2230 Blatt 1 (2003), Systematic calculation of highly stressed bolted joints – Joints with one cylindrical bolt." The Japan Research Institute for Screw Threads and Fasteners, 2006, pp.57-60 (in Japanese)