Fabrication and performance testing of a 1-kW-class high-temperature superconducting generator with a high-temperature superconducting contactless field exciter

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Abstract

This paper deals with the fabrication and performance testing of a prototype machine for the world’s first implementation of a new type high-temperature superconducting rotating machine (HTSRM), which is charged and operated by the application of a contactless superconducting excitation technique with a rotary-type HTS flux pump based on a permanent magnet. Although this type of flux pump has been actively applied in stationary superconducting applications, its practical demonstration on rotary superconducting applications, namely, rotating machines, has not yet been conducted or reported. Therefore, laboratory-scale hardware implementation was conducted to investigate the feasibility of using an HTS contactless field exciter (CFE) as the field exciter of an HTSRM. Firstly, the various core components were manufactured, assembled, and tested to configure the 1-kW-class high-temperature superconducting generator (HTSG) system. Then, the assembled machine was connected with a conventional induction motor and three-phase resistive load. In non-load tests, the characteristics of the induced voltage of the HTSG, which was generated and affected by contactless field excitation and the operating speed, respectively, were tested and measured. In particular, the charge and discharge behaviors of the field current excited by the HTS CFE were experimentally analyzed based on the induced voltage profiles of the HTSG. Then, the HTSG output characteristics were tested and measured by performing experiments on the characteristics of constant load and constant speed, respectively. The generator test results were satisfactory in terms of output, voltage regulation, and the total harmonic distortion in the voltage and current.

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Our developed HTS CFE can excite an HTS field coil with 101 A in a noncontact manner, resulting in an operating field current margin of approximately 79% and a decrease of approximately 91.5% in the field excitation loss. In addition, the results demonstrated the possibility of designing HTS magnets with self-protecting features.

Keywords: contactless field exciter, high-temperature superconducting generator (HTSG), rotary-type HTS flux pump, second-generation HTS field coil

(Some figures may appear in colour only in the online journal)

1. Introduction

High-temperature superconducting (HTS) conductors are highly suitable for large-scale rotating machinery that requires high energy density, such as low-speed and high-torque rotating machines, viz., direct drive-type generators for off-shore wind turbines and propulsion motors for electric ships. Among HTS conductors, rare-earth barium copper oxide tape, which is a second generation (2G) coated conductor, provides high current density to rotor-field coils (FCs), resulting in machines with smaller volumes and lower weights than conventional rotating machinery of equal capacity. However, to achieve these objectives, electrical and mechanical connections are required between a direct current (DC) power supply (PS) at room temperature and an FC at cryogenic temperature through a slip-ring/brush set and metal current leads. The use of such DC current leads results in additional thermal losses, i.e. thermal conduction and ohmic Joule heating losses, in HTS FCs. These losses decrease the coil stability and increase the cooling load.

This paper presents the practical results of the fabrication and performance testing of a 1-kW-class high-temperature superconducting generator (HTSG) that is charged and operated by a noncontact excitation system, i.e. an HTS contactless field exciter (CFE). This exciter originates from the so-called rotating magnet-based HTS flux pump and is a noncontact PS for superconducting DC magnets [1–13]. A flux pump, which has been actively utilized in stationary superconducting applications as a current exciter, can completely block the thermal intrusion from conventional contact-type excitation devices at room temperature and strongly suppress the internal Joule heating during current excitation. These characteristics indicate that higher efficiency and stability can be achieved in HTS DC magnets than via mechanical contact excitation.

For rotary superconducting applications, the slip-ring/brush set, metal current lead, and external PS included in the contact excitation system can be eliminated by the system generating and supplying its own DC power inside the HTS rotor. Thus, this apparatus enables high efficiency, strong reliability, and cost savings in superconducting rotating machine systems by removing the mechanical connection between the contact excitation system at room temperature. In particular, it almost completely eliminates the thermal load generated at the metal current leads and provides the HTS FCs with high electrical and thermal stabilities.

Despite the abovementioned technical advantages, practical demonstration of the use of an HTS noncontact excitation system in rotary superconducting applications, specifically, HTS rotating machines (HTSRMs), has not yet been conducted or reported on because the application of flux pumps to rotating superconducting field coils is technically more difficult than that of stationary superconducting magnets. The design of a flux pump structure, which should be integrated with a cylindrical rotor and electrically compatible with the HTS field coils, is a challenge that should be addressed to develop an optimized HTS rotor. Clearly, a suitable flux pump design should be confirmed through practical development and testing to determine its applicability intuitively. Therefore, in the present study, we focused on the design, fabrication, and operating performance testing of a 1-kW-class HTSG to confirm the technical feasibility of using the contactless excitation method on an HTSRM. The HTSG was designed and analyzed in our previous studies [14–24]. Moreover, a full-scale HTS field pole and HTS CFE were developed and experimentally tested to investigate their fundamental operating performance characteristics [14].

In this study, the various core components of the HTS generator, such as a salient rotor pole with HTS coils, rotating shafts, torque-transferring structures, rotating and stationary parts for the CFE, and a liquid nitrogen (LN2) cooling system, were manufactured and assembled to configure the 1-kW-class HTSG system. HTS rotor components, such as rotor field poles and toroidal rotors of the CFE, were assembled. The contactless field-excitation performance of the apparatus was verified before the final assembly of the HTSG system. The HTSG stator was fabricated with three-phase copper armature winding based on two-dimensional (2D) finite element analysis. In addition, a cryogenic cooling system using LN2 was fabricated and its cooling characteristics were tested in connection with the HTSG.

Next, a motor–generator (M-G) set was developed using a commercial 5.5 kW induction motor and the developed 1-kW-class HTSG. The HTSG operating performance was evaluated using the M-G test setup. The open-circuit induced voltage ($E_i$) of the HTSG, which is generated and affected by contactless field excitation and the operating speed, was tested and measured using a non-load test. Then, in a load test, three-phase variable resistive loads were connected. The HTSG output characteristics were tested and measured by conducting tests of the constant speed characteristic (CSC) and constant load characteristic (CLC).
2. Design and fabrication

Figure 1 shows the three-dimensional (3D) configuration of the 2G HTS CFE and its corresponding equivalent R-L circuit. A 2G HTS flux pump based on a rotating magnet is considered as the DC generator or DC PS, which is equipped with rectifier circuits and operates at 77 K. The time-varying magnetic field from the permanent magnets (PMs) in the stationary part at room temperature, in general 300 K, penetrates into 2G HTS wires in the rotary part at cryogenic temperature due to the relative rotation of the rotor. Then, a partially rectified open circuit voltage ($V_{oc}$), i.e. quasi-DC voltage, is induced at the 2G HTS wires and drives current into the HTS load coil, as shown in figure 1(b). This current is electrically governed as follows [7, 8, 12, 13]:

$$I_t(t) = \frac{V_{oc}}{R_e} \left( 1 - e^{-\frac{R_e}{L_c}t} \right) = I_{sc} \left( 1 - e^{-\frac{R_e}{L_c}t} \right)$$

where $R_e$ is the total resistance in the superconducting loop, being the sum of dynamic resistance ($R_d$) and the resistance of the soldered joints ($R_j$), i.e. $R_e = R_j + R_d$. $L_c$ denotes the inductance of the HTS coil for the electric load. Moreover, $L_c/R_e$ denotes a time constant $\tau$, which determines the charge time to reach the ramped-up $I_t$. The charged field current ($I_t$) is defined as $V_{oc}/R_e$ and is the maximum available current that can be transferred into the loaded HTS coil by the HTS flux pump. More details on the fundamental mechanism of the 2G HTS flux pump are provided in [10–13].

Figure 2 presents photographs of the HTS rotor assembly of the 1-kW-class HTSG. An HTS CFE toroidal rotor head is uniaxially connected to the HTS field-pole. The eight HTS strands are wound around the toroidal head and joined in series with HTS FCs. T-shaped PMs in the CFE stator are aligned with the center of the toroidal head and inject the time-varying magnetic field into the HTS strands. Thus, eight quasi-DC
Figure 3. Noncontact charging profiles of $I_f$ at rotating speed of 100 rpm and 200 rpm.

Figure 4. Charging and sudden-discharging characteristics of the second poles at 10 A and 90 A.
Figure 5. Charging and discharging $I_f$ profiles obtained using a 100-A-class HTS CFE. (a) Before re-winding HTS wire on CFE, (b) after re-winding HTS wire on CFE, and (c) comparison of normalized discharging $I_f$.

Voltage sources are generated that excite the HTS FCs. Details regarding the design, fabrication, and characteristic tests of the HTS rotor assembly are presented in [14, 15]. In particular, a contactless current charging test was preferentially conducted and its charging performance was successfully verified, as described in [14].

Figure 3 shows the preliminary noncontact current excitation results of four full-scale FCs connected in series according to charge speed. The fully saturated current ($I_s$) is approximately 70 A at both charge speeds. Increasing the charge speed from 100 rpm to 200 rpm decreases the charge time from approximately 530.89 s to 306.82 s, which corresponds to the definition of $\tau$, i.e. the time required to reach 63.2% of the fully saturated current. This enhancement in charge speed is caused by increase in $R_d$ at a charge speed of 200 rpm, i.e. $\downarrow \tau = L_c/\uparrow R_d (= \uparrow R_d + R_j)$. The $R_d$ values estimated from figure 3 are 61.11 $\mu\Omega$ and 106.36 $\mu\Omega$ at 100 rpm and 200 rpm, respectively.

The black dashed circle in figure 3 implies the possibility of designing a 2G HTS magnet with a self-protecting feature because it shows that the current charge is temporarily held when the LN2 level is low inside the cryostat. Specifically, the slope of $I_f$ temporarily decreases, as shown by the red line with circles in figure 3. This tendency occurs because the R-L circuit composed of the HTS CFE and HTS FCs cannot be thermally maintained in the superconducting state owing to...
| Parameters | Unit | Value |
|------------|------|-------|
| **HTS Synchronous Generator** | | |
| Machine type | – | Rotary HTS field /Stationary Cu armature |
| Rated power | kW | 1 |
| Rated rotating speed | rpm | 400 |
| Number of field pole | – | 4 |
| Number of stator slots | – | 48 |
| **HTS Field Pole** | | |
| Field pole type | – | Salient pole with S45 C |
| Field coil type | – | Racetrack HTS SPC |
| Used 2G HTS conductor | – | SCS 12050 (SuperPower) |
| Conductor width/thickness | mm | 12/0.064 |
| Insulation materials | – | Kapton Polyimide film |
| Winding turns per SPC | – | 60 |
| Total conductor length | m | 120 |
| Total coil inductance $L_c$ | mH | 32.9 |
| Operating temperature | K | 77 |
| Critical current $I_c$/n-value | A— | Four FCs: 128/26 |
| **HTS Field Exciter** | | |
| Excitation source /method | – | DC voltage source /Noncontact method |
| Exciter type | – | Rotary HTS flux pump |
| Exciter assignment | – | Single CFE to four-FCs |
| Capacity | A | 100 |
| Operating temperature | K | 77 |
| Excitation loss at 70.4 A/101 A | W | 0.54/1.11 |
| Operating current margin ($I_f/I_c$) | – | 0.789 |
| Connection to FC | – | Series |
| Used 2 G HTS conductor / PM types | – | SCN12550 (SuNAM) /NdFeB N50 |

Figure 6. Photographs of HTS rotor assembly I. (a) Before epoxy impregnation, (b) after epoxy impregnation, and (c) covering by SUS-cylinder.
insufficient cooling, which is caused by a shortage of LN2, particularly at the CFE rotor. The slope is recovered with the refilling of LN2 into the cryostat. Such behavior is technically attractive for stable operation of the 2G HTS magnet because it can be considered as a self-protecting characteristic. When HTS magnets are charged using the contact-type excitation method, i.e. the constant current mode of the DC PS, they may be permanently damaged by an operating current \( I_{op} \) above the critical current \( I_c \) if the PS does not provide reliable current control according to the cooling state of the HTS coil, i.e. changes in the operating temperature \( T_{op} \). However, when HTS magnets are charged using the contactless excitation method, i.e. the HTS CFE, the HTS magnets can reduce the charge current, i.e. \( I_{op} \), by themselves and protect themselves from permanent damage even if the cooling conditions are not suitable in terms of \( T_{op} \). This feature should be investigated in detail in the future for more complete understanding.

Before the final rotor assembly, Hall sensors were calibrated with epoxy impregnation to measure the Hall signals at a constant position. Using a DC PS, magnetic field density profiles were measured at charges of 10 A and 90 A, as shown in figure 4. Thus, \( I_f \) could be indirectly predicted using Hall voltage signals corresponding to the magnetic field these charges. Finally, using the Hall voltage in the second pole, the \( I_f \) profile was measured at 16 PMs, an air gap of 8 mm, and a charge speed of 200 rpm, as shown in figure 5(b). \( I_f \)
was fully saturated around 101 A, and this value was approximately 32.3% higher than that obtained in the preliminary charging test described in [14]. The charging time required to reach 101 A was 887 s, and the current ramp-up rate was 0.114 A s\(^{-1}\). It was concluded that this increment in \(I_f\) is attributable to the joint resistances in the superconducting closed-circuit being decreased by re-winding, thereby causing re-soldering between the two ends of the HTS strand in the CFE and HTS coils in the field pole and replacement with new 2G HTS wires. This supposition can be reasonably proven by normalized comparison of the spontaneous discharged currents, as shown in figure 5(c). The \(I_f\) profile before re-winding the HTS wire is represented by the red curve in figure 5(a). The black curve, i.e. the discharging profile after the re-joint between the HTS CFE and HTS field pole, depicts slower discharging than the red curve, due to the lower joint resistances in the superconducting circuit.

Considering HTS FC charging with currents of 70.4 A and 101 A using a contact excitation system, the excitation losses in the current lead pairs with round rods were estimated to be 8.46 W and 13 W, respectively, assuming a 330 mm axial length, 3.1 mm diameter, 9.87 n\(\Omega\)m resistivity, and 411 W mK\(^{-1}\) thermal conductivity of Cu at 77 K. However, considering charging of the HTS FCs by the HTS CFE, the excitation losses were estimated to be 0.54 W and 1.11 W, respectively, assuming the total resistance of the superconducting circuit inside the HTS rotor \(R_e\) to be 107.23 \(\mu\Omega\) and 107.12 \(\mu\Omega\), respectively. The values of \(R_e\) (=\(L_e/\tau\)) could be roughly calculated using the \(I_f\) charging profiles, as shown in figure 5. In an equal operating environment, the HTS CFE is expected to reduce the excitation loss by approximately 93.7% and 91.5%, respectively, compared to the conventional contact excitation system. The final key parameters of the 1-kW-class HTSG are summarized in table 1.

Figure 6 presents photographs of the rotor assembly without the rotating shafts and cryostat. The joint lead wires, which connect the HTS CFE and field pole, and the various signal wires were impregnated with Stycast epoxy to protect them mechanically from the whirlpool of LN2 when the HTSG rotated. This assembly was finally covered and welded using a stainless steel (SS) cylinder to contain the LN2. The entire rotor assembly of the 1-kW-class HTSG was successfully fabricated using the connection of a bellows pipe, torque transferring structures, rotating shafts, and a cryostat, as shown in figure 7. The bellows pipe, which contains the cooling pipe, was connected at the pole-end body with indium sealing. Then, the rotating shafts were assembled at both rotor ends through the torque tube and disk, as shown in figure 7(c). The assembly of the HTS rotor was completed by covering it with a cryostat and connecting the signal feedthrough and vacuum seal-off valve.

3. Test results and discussion

3.1. Performance test setup

Since an expensive dynamometer was required to measure the output performance of the HTSRM in the motor operation mode, the generator operation mode was employed to configure the performance test environment.

The M-G setup was finally assembled using a commercial 5.5 kW induction motor, the developed 1-kW-class HTSG, and the cryogenic cooling system. A simple cooling system was considered to inject LN2 into the HTS rotor without using any complex devices for generation and circulation of the cryogen. Figure 8 shows the configuration of the cryogenic cooling system using LN2; it was empirically designed and fabricated based on similar devices employed in previous studies [25–28]. The cooling system was composed of an LN2 cryostat outside the generator and a triple cooling pipe inside. Because direct injection of LN2 through the original pressure of the LN2 dewar could thermally and mechanically
damage the ferrofluid seal, the additional cryostat was used to construct the cryogenic cooling system, which could manually control the injection pressure of the LN2 stored in the cryogenic vessel. Using the pressure of gaseous nitrogen (GN2) in an external tank or naturally vaporized GN2 in the LN2 cryostat, which are lower than the original pressure of the LN2 dewar, LN2 can be supplied to the LN2 feeding pipe inside the HTSG. The more details about design, fabrication, and test of the developed LN2 cooling system have been reported in [15, 29].

Figure 9 shows the configuration of the test setup used to measure the operation characteristics of the 1-kW-class HTSG. In the initial field-charging mode, $I_f$ begins charging via a noncontact method owing to injection of the time-varying magnetic field by the HTS CFE rotor rotation, which is uniaxially connected with the HTSG field pole. The maximum $I_s$ in the field winding can be controlled by the rotating speed ($N_s$) in charging mode. Therefore, to control $I_s$ in the field winding as well as $E_f$ of the HTSG, a prime mover (induction motor) was driven and controlled by an inverter with variable speed control. The load characteristics of the 1-kW-class HTSG were experimentally analyzed by measuring the electrical output parameters, such as the phase voltage ($V_p$), voltage regulation ($V_r$), phase current ($I_p$), active power ($P_a$), and total harmonic distortions (THDs) in the $V_p$ and $I_p$.

The variable HTSG output signals were measured and monitored using an oscilloscope (HDO 4034 A, Teledyne LeCroy Co.) and a power quality analyzer (DEWE-571, Dewetron, Inc.). The cooling condition inside the HTS rotor...
and the stability of the field winding were detected through the temperature sensors in the field pole and the terminal voltages in four HTS single pancake coils (SPCs). All of the signals inside the rotor were drawn through the slip ring and brush set, which were coupled to a hollow shaft. They were monitored and recorded in the external PC data acquisition system.

3.2. Non-load test

As technical problems in the slip ring and brush set occurred during the rotation test, no output signals in the HTS rotor could be measured during the generator test. The behavior of the measured $E_i$ of HTSG was therefore analyzed to explain the test results reasonably without any $I_f$ signals. In general,
$E_i$ of the synchronous generator is proportional to the mechanical constant ($K$), $N_s$, and magnetic flux ($\Phi$) or $I_f$, i.e. $E_i = K\Phi(I_f)N_s$, before the iron cores are magnetically saturated. In other words, if $N_s$ is continuously maintained during the elapsed time, $E_i$ of the HTSG would also exhibit the same behavior with $I_f$ charged by the HTS CFE.

Through speed-up and speed-down tests without the resistive load, output data were measured and recorded continuously for 7 h using a power quality analyzer and oscilloscope. Figure 10 shows the profiles of $E_i$. They were generated in the open-circuited three-phase armature and measured as the root mean square values with respect to the power quality analyzer. After disconnecting the circuit breaker for switching to the resistive load, the HTSG three-phase $E_i$ was observed at successive values of $N_s$.

In the speed-up tests, $N_s$ was increased from 200 rpm up to 900 rpm in 100 rpm increments after $E_i$ of HTSG was saturated and observed using the measurement devices. In the initial operation, the HTSG was operated at 100 rpm to cool the rotor inside. Then, $N_s$ was increased and constantly maintained at 200 rpm after 3200 s to excite the HTS FCs fully.

With 200 rpm rotation, despite $N_s$ remaining constant until 6000 s, $E_i$ of the HTSG increased continuously, as shown in the black-dotted square in figure 10. Thus, $I_f$ charged by the HTS CFE was not saturated and exponentially increased to the $I_f$ saturation zone. $E_i$ of the HTSG was almost saturated and then maintained by the saturated $I_f$ for approximately 6000 s. The value of $I_s$ was expected to be 101 A based on the final current charging test, as shown in figure 5(b).

In the speed-up tests from 200 rpm to 600 rpm, whenever $N_s$ of the HTSG was increased to 600 rpm, $E_i$ remained constant or slightly increased during the elapsed time. This behavior indicates that $I_f$ was charged at a constant or slightly higher rate, i.e. $I_f \geq 101$ A, as shown in the enlarged view of the region enclosed within the blue dashed square in figure 10. The magnitude of $E_i$, which increases with each speed acceleration, is almost constant. Therefore, only the increase in $N_s$ appears to affect the changes in $E_i$ of the HTSG, as shown.

Figure 12. Measurement screens in non-load test. (a) Output characteristics in power quality analyzer and (b) $E_i$ waveforms in oscilloscope.
in figure 11. In summary, the maximum \( I_f \) was charged and saturated with \( N_s = 600 \text{ rpm} \) and the operating current margin, which is defined as the ratio of \( I_c \) to \( I_f \), was calculated to be 0.789. The charge behaviors with \( N_s \) from 200 up to 600 rpm

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**Figure 13.** Characteristic comparison of experiment- and FEA-results in non-loaded test and estimation results on the \( I_c \), respectively.

**Table 2.** CSC test performance results.

| \( N_s \) [rpm] | \( R^a \) [Ω] | \( V_p^a \) [Vrms] | \( V_r^a \) [%] | \( I_p^a \) [Arms] | \( P_a \) [W] | VTHD\(^a\) /ITHD\(^a\) [%] |
|-----------------|--------------|-------------------|----------------|---------------|-------------|---------------------|
| 200             | 404          | 116               | 9.77           | 0.32          | 102.0       | 1.07/1.60          |
| 200             | 303          | 114               | 11.46          | 0.41          | 131.0       | 1.15/1.43          |
| 200             | 200          | 114.8             | 10.16          | 0.60          | 201.0       | 1.09/1.24          |
| 200             | 150          | 112.4             | 12.62          | 0.78          | 259.7       | 1.11/1.21          |
| 200             | 100          | 112               | 14.18          | 1.22          | 404.8       | 1.02/1.04          |
| 300             | 396          | 174               | 5.75           | 0.46          | 231.3       | 0.93/1.19          |
| 300             | 303          | 175.2             | 4.69           | 0.60          | 307.5       | 0.93/1.02          |
| 300             | 202          | 173.9             | 7.23           | 0.89          | 460.6       | 0.91/0.97          |
| 300             | 152          | 170.7             | 7.17           | 1.18          | 597.8       | 0.90/0.91          |
| 300             | 99           | 167.8             | 9.62           | 1.83          | 916.7       | 0.87/0.88          |
| 400             | 405          | 232.4             | 3.44           | 0.59          | 404.1       | 0.90/0.94          |
| 400             | 303          | 232.8             | 2.70           | 0.79          | 542.3       | 0.88/0.89          |
| 400             | 203          | 230.3             | 4.99           | 1.17          | 801.8       | 0.88/0.88          |
| 400             | 150          | 229.3             | 4.48           | 1.58          | 1085.6      | 0.86/0.85          |
| 500             | 400          | 289.2             | 2.36           | 0.74          | 630.4       | 0.86/0.87          |
| 500             | 300          | 289               | 2.34           | 0.97          | 833.5       | 0.86/0.85          |
| 500             | 203          | 287.9             | 2.71           | 1.42          | 1225.5      | 0.85/0.85          |
| 600             | 406          | 348.2             | 1.22           | 0.87          | 898.3       | 0.86/0.91          |
| 600             | 302          | 347.4             | 1.55           | 1.15          | 1196.5      | 0.85/0.89          |
| 600             | 203          | 345.4             | 2.19           | 1.72          | 1778.9      | 0.84/0.85          |
| 700             | 391          | 398.4             | 1.03           | 1.00          | 1190.7      | 0.86/0.88          |
| 700             | 302          | 399.0             | 1.06           | 1.30          | 1554.3      | 0.85/0.86          |
| 800             | 395          | 443.8             | 0.66           | 1.12          | 1484.9      | 0.89/0.91          |
| 800             | 350          | 441.9             | 0.89           | 1.26          | 1661.3      | 0.87/0.88          |

\( ^a \) Average value over three phases
Figure 14. Profiles of output parameters with $N_s$ of (a) 200 rpm, (b) 400 rpm, (c) 600 rpm, and (d) 800 rpm in the CSC test.
suggest that the unchanging characteristic of $I_f$ within certain $N_s$ of the developed CFE is suitable for industrial applications that require constant-speed operation because the developed HTSG is operated like a PM generator or motor, which have constant main magnetic fields from the PM field pole, within a certain speed range.

Figure 12 shows the measurement results obtained from DEWE-571 and HDO 4034 A devices. The average $E_i$ of the three phases was measured to be 238 Vrms at the rated speed, i.e. 400 rpm.

In the speed-up tests from 700 rpm to 900 rpm, although $N_s$ was constant at the beginning of the speed changes, $E_i$ exponentially decreased to a certain value after reaching the maximum value, as shown in the enlarged view of the region contained within the red dashed square in figure 10. This tendency is believed to be due to the decrease of $I_f$ from its initial value. It can be assumed to be the demagnetizing effect due to automatic field weakening control in HTS FCs at high speeds. It is reasonably proven by the slope decrease in the curve of $E_i$ versus $N_s$, as shown in the red dashed circle in figure 11. The inherent charging characteristic of the HTS flux pump, which is the amount of current charging that can be reduced under high speeds, or the uneven cooling of the rotor due to excessive centrifugal force during high-speed rotation, is considered to be a cause of this phenomenon. In [8, 30–33], such anomalous behaviors were reasonably expected to be caused by eddy currents at higher $N_s$, leading to heat loss in iron structures and 2G HTS wires and resulting in $V_{oc}$ and $R_d$ reduction by decreasing the linkage flux and $I_c$, respectively. Moreover, the automatic demagnetizing effect due to decreasing $I_f$ can be applied to HTS motors for electric traction and propulsion, which require field weakening control during high-speed
operation. For \( N_s \) of 600 rpm and above, \( I_t \) was expected to decrease to 101 A or less, and the minimum \( I_t \) was charged and saturated at \( N_s = 900 \) rpm.

In the speed-down tests, \( N_s \) was set to decrease from 900 rpm to 200 rpm in 100 rpm intervals after \( E_i \) of the HTSG was saturated. In the speed-down tests from 900 rpm to 700 rpm, although \( N_s \) of the HTSG was constant at the beginning of the speed changes, \( E_i \) increased exponentially to a certain value after reaching the minimum value, as shown in the enlarged view of the region within the red-dashed square in figure 10. It can be concluded that this tendency was caused by the increase of \( I_t \) from its initial value. That is, it was a behavior through which \( I_t \), which was saturated to the minimum value at 900 rpm, was re-charged at 800 rpm or 700 rpm above \( I_s \) at 900 rpm.

In the speed-down tests from 600 rpm to 200 rpm, \( E_i \) of the HTSG at each \( N_s \) had the same value as in the speed-up tests. Moreover, at the magnitude of \( E_i \), which decreased with each speed drop, i.e. the slope of the \( E_i \) curve, was also constant, as shown in figure 11. Therefore, only \( N_s \) affected the changes in \( E_i \) of the HTSG.

To understand the \( I_t \) behaviors more reasonably, the values of \( I_t \) were inversely estimated based on test results of the \( E_i \) using 2D FEA. Figure 13 shows the \( E_i \) and \( I_t \) profiles to compare the experimental approach with the numerical method. It is observed that the values of \( N_s \), which are same in the \( x \) axis of figure 11, were used for 2D FE simulations to compare both results in equal operating conditions. Generally, difference in analysis results as compared to those of experiments was observed. It attributes this difference to the measurement errors for various output signal in experiments, as well as difference in the material property of magnetic cores. The difference in \( E_i \) between experiment and simulation is approximately 12 \( V_{rms} \), thereby indicating that the \( E_i \) values in the experiment (\( E_{ic} \): red line with square symbol, \( E_{ig} \): green line with circle symbol, and \( E_{it} \): red line with triangle symbol) was 12 \( V_{rms} \) higher than those of simulations (\( E_i \): violet line with inverse triangle symbol) on an average, as shown in figure 13. The values of saturated \( I_t \) are conversely estimated based on the \( E_i \) profile in the experiment, as shown by the blue line with square symbol in figure 13 and presented in figure 13. For values of \( N_s \) between 700 and 900 rpm, it was observed that saturated \( I_t \) decreases for each value of \( N_s \). The values of \( I_t \) at 700, 800, and 900 rpm were estimated to be 96, 88, and 76 A, respectively.

3.3. Load test

The operating performance of the 1-kW-class HTSG was verified by measuring the electrical outputs supplied to the three-phase variable resistive load with a capacity of 1.5 kW connected to the HTSG stator. Through the resistive load test, the continuous outputs for a total of 5 h were measured and recorded with a power-quality analyzer and oscilloscope. The CSC test was conducted with a constant \( N_s \) and variable load resistance \( R_l \). When \( E_i \) and \( I_t \) of the HTSG were fully saturated by the rotation with constant \( N_s \), the load test was conducted by inputting \( R_l \) and changing \( R_t \). The output parameters, i.e. \( V_p \), \( V_l \), \( I_p \), \( P_a \), the THDs, and others were measured from 200 rpm to 800 rpm in 100 rpm intervals; these values are listed in table 2. Figure 14 shows the profiles of the various output parameters that were generated in the CSC test and measured as root mean square values in the power quality analyzer. The rated \( P_a \) of the HTSG, i.e. 1086 W, was generated with \( I_p = 1.58 \) A, \( N_s = 400 \) rpm, and \( R_l = 150 \) \( \Omega \) in the CSC test. Moreover, the THDs in \( V_p \), \( I_p \), and \( V_l \) were measured to be 0.86%, 0.85%, and 4.48%, respectively, at the rated output. The maximum \( P_a \) of 1779 W was confirmed at \( N_s = 600 \) rpm and \( R_l = 203 \) \( \Omega \) in the CSC tests. The maximum \( J_p \) with \( I_p = 1.72 \) A was calculated to be 1.21 A mm\(^{-2}\). The THDs in both \( V_p \) and \( I_p \) were measured to be approximately 1% in the overall test ranges and were less than 1% when \( N_s \) was greater than 400 rpm. Through the experimental validation of the superior THDs in the \( V_p \) and \( I_p \) outputs (both at the 1% level), it was concluded that the current ripple of pulsating field excitation, which arises from the HTS CFE, does not adversely
affect the output characteristic of an HTSRM [34]. The output characteristics at \( N_s = 400 \text{ rpm} \) and \( R_l = 150 \Omega \) were measured and screened from DEWE-571 and HDO 4034 A devices, as shown in figure 15.

The CLC test was conducted with constant \( R_l \) and variable \( N_s \), as shown in figure 16. When \( E_i \) and \( I_s \) of the HTSG were fully saturated by rotation at a constant speed, the load test was conducted by inputting constant \( R_l \) and changing \( N_s \).

4. Conclusion

In this study, a 1-kW-class HTSG charged and operated by a noncontact excitation system, i.e. an HTS CFE, was successfully developed and tested in an M-G test setup. This development is technically meaningful because it is the world’s first demonstration of the application of a rotating magnet-based HTS flux pump to an HTS rotating machine. The core components of the HTSG were designed and fabricated, and the basic performance was tested before the HTSG system was fully assembled. Finally, the M-G test setup was constructed to investigate the operating characteristics of the 1-kW-class HTSG, and the application feasibility of the HTS CFE was confirmed through various performance tests.

The noncontact current charging performance of the HTS FCs was successfully demonstrated at a charging speed of 53.3 Hz in the HTS CFE, i.e. \( f_s \), as shown in figure 15. When \( E_i \) and \( I_s \) of the HTSG were fully saturated by rotation at a constant speed, the load test was conducted by inputting constant \( R_l \) and changing \( N_s \).

(a) The application of a demagnetizing effect at high speeds on field-weakening control for HTS traction and propulsion may be possible, including optimization design for rated operating points, i.e. field current, speed, armature voltage, and etc.

(b) Ripple-pulsating field excitation does not affect the output characteristic of an HTSRM.

It is believed that the practical results presented in this paper can contribute to the relevant research on excitation systems for HTSRMs. However, technical limitations remain to be addressed in terms of current controllability. These limitations should be overcome to respond to startup and load changes in the transient operation of HTS generators or motors. In a future study, a scaled-up HTSG system, equipped with an electromagnet-type HTS CFE to control the excitation on HTS FCs actively, will be developed.

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