Analysis Stability of Cable-In-Conduit-Conductor with NbTi Superconducting Strands of Various Cu/SC Ratios Used in PF6 of KSTAR

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Abstract--**The stability of PF 6-7 has been studied according to the transient analysis code TOKSCPF and quench analysis code QSAIT. We compare the stability and temperature rise with various Cu/SC ratios of 2.8 and 3.5 under the KSTAR normal operating conditions. It shows that the Cu/SC ratio has an influence on the quench propagation and stability margin. In transient operating condition, the Cu/SC ratio weakly influences on the temperature rise in PF magnet.**

I. INTRODUCTION

The Korea Superconducting Tokamak Advanced Research (KSTAR) program is a full superconducting Tokamak device with the central magnetic field of 3.5 T at the major plasma radius of 1.8 m. The Tokamak adopts the cable-in-conduit conductor (CICC) as the basic elements for the TF and PF superconducting magnets. The Cu/SC ratio in the superconducting strands of the NbTi/Cu in the CICC for the PF6 and 7 magnets have a great influence on the stability and cost of magnet system. The suitable Cu/SC ratio and strand number of the superconducting wire are studied for the Cable-in-Conduit-Conductor. In the analysis, following scenarios are considered :

Case1: Cu/SC ratio of 3.5 in the NbTi composite strands and $2N_{strands}/3$ superconducting strands in the CICC.

Case 2: Cu/SC ratio of 2.8 in the NbTi composite strands and $2N_{strands}/3$ superconducting strands in the CICC.

II. DESIGN CRITERIA, CRITICAL CURRENT AND MARGIN OF OPERATING CURRENT

The KSTAR superconducting Tokamak design criteria are shown in Table-I. The criteria can guarantee the superconducting magnet to remain superconducting state and recover without quench during all modes of normal operation, from all disturbances, including disruptions occurring at any time[1].

TABLE-I
KSTAR DESIGN CRITERIA

Parameter	Units	Allowable
$T_{margin/headroom}$	(K)	1.0/2.0
$f_{Critical}$	(-)	0.6
$E_{margin/headroom}$	(mJ/CC)	300/600
h_{I2R}	(W/m^2-K)	600 (NbTi)
Tmax	(K)	150
Vterm	(kV)	15
$h_{distribution}$	(W/ m^2-K)	640

The main operating conditions for the PF6 superconducting magnet are listed in TABLE II. The parameters for the calculation of critical current density of NbTi are listed in Table-III. The parameters are from Gandalf code. The calculation formulae of NbTi critical current density is[2]

$$J_C = \frac{C_0}{B} B_{lcase}^{\alpha}\left(1 - B_{lcase}\right)^{\beta}\left(1 - T_{lcase}^{N}\right)^{\gamma} \quad (1)$$

where $T_{lcase} = \dfrac{T}{T_{C0}}, B_{lcase} = B / B_{C2}$ and

$$B_{c2} = B_{c20}\left(1 - T / T_{Co}\right)^{N}$$

Based on the equation, the critical current density of NbTi at 2 T and 5 K is $J_C = 3.566\times10^9$ A/m^2 (The critical current density of NbTi is $J_C = 4.62365\times10^9$ A/m^2 based on Tokscpf)

Assumption the Cu/SC ratio in the NbTi superconducting composition wire is f_{CuSC} and f_{pure} is the ratio of pure copper strands/total strands in the CICC. The total strands number including the superconducting wire and pure copper strands number is $N_{Strands}$. The cross-sectional area of NbTi strand is the same as that of the pure copper strands. A single strand cross-sectional area is

$$A = \pi\left(\frac{d}{2}\right)^2 = 3.14 \times \left(\frac{0.78}{2}\right)^2 = 0.477594 \ mm^2 \quad (2)$$

Total cross-sectional areas of superconductor and copper are, respectively

$$\varepsilon_{opl} = \frac{I_{opt}}{I_C} \quad (3)$$

$$\left(Cu / SC\right)_{CICC} = \frac{A_{Cu}}{A_{SC}} \quad (4)$$

The critical current, Cu/SC ratio in the CICC and ratio of the operating currents to their critical currents are listed in the TABLE-IV.

TABLE -II
Operating conditions for the PF-6

Maximum operating current	20.0 kA	Maximum operating field	2 Tesla
Operating temperature	5-5.5 K	Operating pressure	5 atm
Strands diameter	0.78 mm	Strands number	360
Cu/SC ratio in NbTi	3.5	pure copper strands number	120
NbTi strands number	240	A_{cu}/A_{SC} in CICC	5.75

TABLE-III
Parameters for the calculation of Critical current density of NbTi

T_{C0M} = 9.5 K,	B_{C20M} =	14.5 T,	C_0	= 5.24×10^{10} A/m^2	
N	=	1.7	α = 0.6	β =	1.0
γ=2.0					

TABLE-IV
Critical current and operating current margin(5K, 2 T and 20 kA)

	A_{Cu} (mm^2)	A_{SC} (mm^2)	A_{Cu}/A_{SC} in CICC	I_C (kA)	I_{OPT}/I_C
Case-1	146.464	25.472	5.75	90.833	22.018%
Case-2	142.48	30.315	4.6998	108.99	18.34%

III. NORMAL OPERATING TRANSIENT STATE FOR KSTAR AND QUENCH SIMULATION

According to the numerical simulation by considering the normal operating transient state of KSTAR and the quench state, the operating scenarios of CICC with strands of Cu/SC = 2.8 and 3.5 are simulated. The normal operating transient state of KSTAR is simulated by using the code of the TOKSCPF and Heater3d for the two cases. The main parameters of the simulation for the PF6 are based on the subroutine KSTAR20pf.

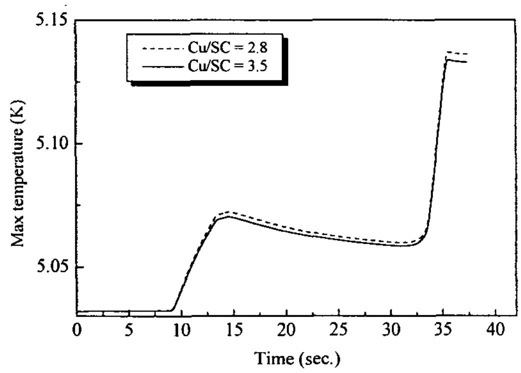

Fig.1 Maximum temperature rise versus time in PF6 for the normal transient operating condition of KSTAR.

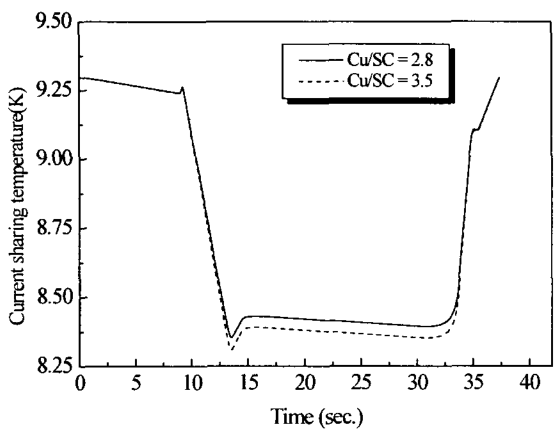

Fig.2 . Minimum current sharing temperature of NbTi/Cu versus time in PF6 for the normal transient operating condition of KSTAR.

Fig.1 shows the maximum temperature versus time for the PF6 superconducting magnet. The maximum temperature of Cu/SC=2.8 is a weakly over than that of Cu/SC=3.5. The minimum current sharing temperature and temperature margin for the PF-6 magnet are illustrated in the Fig. 2 and 3. The maximum different values of the minimum current sharing temperature and operating temperature margin are 0.043 K. The minimum current sharing temperature and temperature margin of case-2 is lower than that of case-1 due to the decrement of the total cross-sectional area of superconductor NbTi in the CICC of PF-6. The inlet helium mass rate for the three cases are plotted in Fig.4

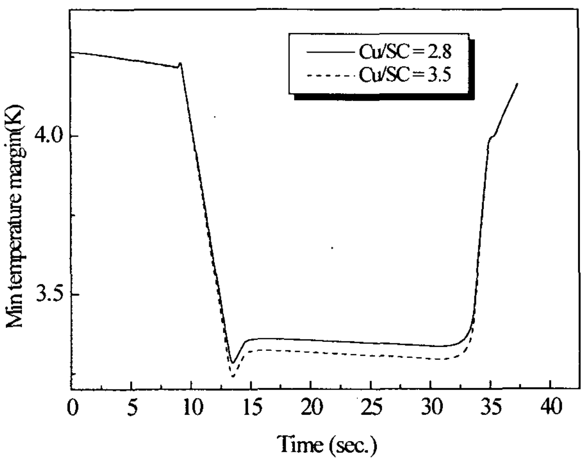

Fig. 3 Minimum temperature margin of NbTi/Cu versus time in PF6 for the normal transient operating condition of KSTAR.

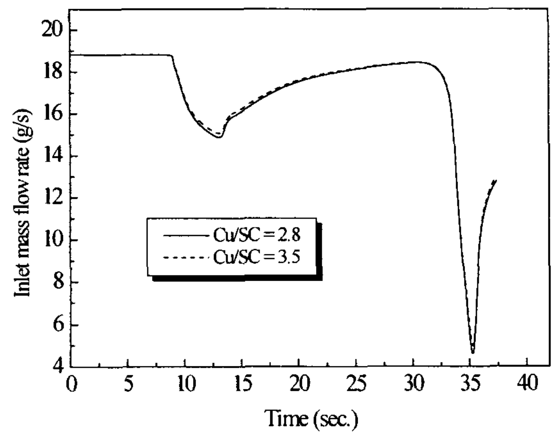

Fig. 4 Inlet mass flow rate of supercritical helium versus time in the PF6 for the normal transient operating condition of KSTAR

The quench simulation is based on the quench analysis code. The CICC parameters are listed as follows Table-V.

Fig.5, 6, 7 and 8 show the normal length, maximum hot-spot temperature rise, supercritical helium pressure and voltage versus time for 5 s quench simulation, respectively. Generally, the different values of case-1 and case-2 are very small. The maximum different values is about < ±3%.

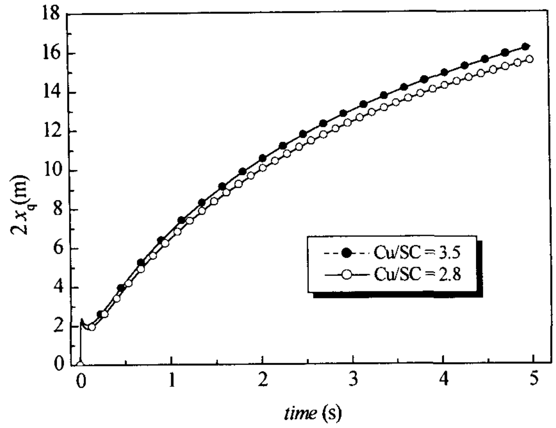

Fig.5 Normal zone length versus time for disturbance duration time of 10 ms and length of 2 m, under the 2 T uniform field and operating current of 20 kA.

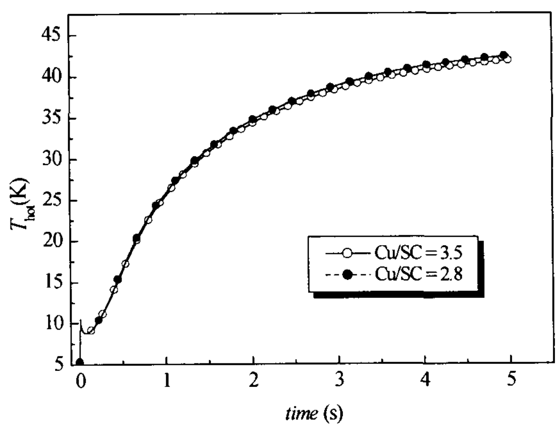

Fig.6 Profiles of hot-spot temperature of conductor versus time for disturbance duration time of 10 ms and length of 2 m, under the 2 T uniform field.

IV. STABILITY MARGIN AND CU/SC RATIO

The Cu/SC ratio in the composite superconducting strand influences on the stability margin. When more copper is added, the strands become more stable for the following reasons: lower average normal zone resistivity results in less Joule heat generation at the normal and the conductor becomes easy to cool. On the other hand, when the more superconductor is employed. The critical current increase and the current density in the superconductor decrease. The result is the temperature margin become larger. It is obvious that strands become more stable when both the copper and the superconductor increase. However, this leads to an increase in the overall cross-sectional area of conductor.

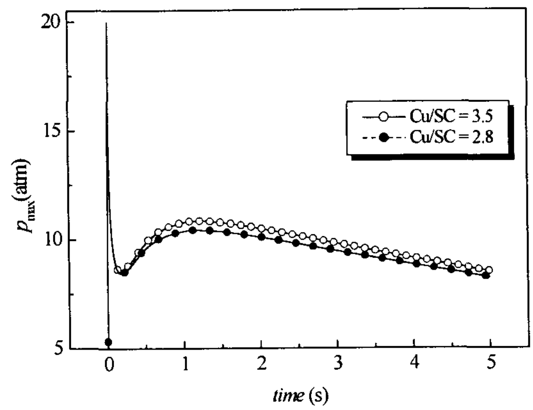

Fig.7 maximum quench pressure versus time foe disturbance duration time of 10 ms and length of 2 m, under the 2 T uniform field.

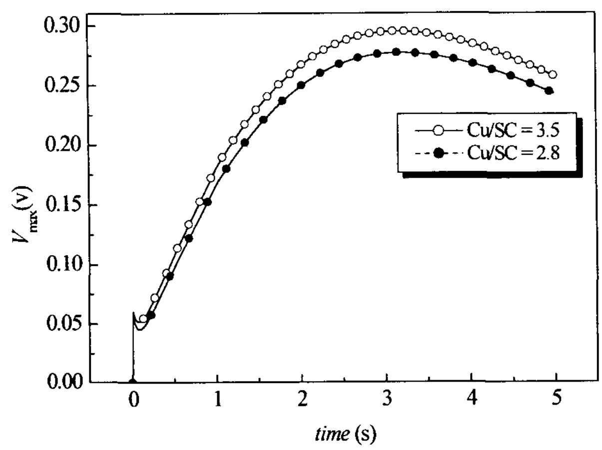

Fig.8 Voltage in the normal zone versus time for disturbance duration time of 10 ms and length of 2 m, under the 2 T uniform field.

TABLE-V

KSTAR - PF6 *coil* (ISC =1, NbTi, ISC =2 Nb3Sn)

GSTEP(s),	dt1(s),	dt2(s),	dt3(s),	t12(s),	t23(s)
1.0,	4.5d-4,	4.5d-4,	4.5d-4,	25d-3,	5.0d-1
duration time(s),	conductor length(m),		disturbance length(m)		
10.0d-3,	230.0,		2.0		
NNODI(-),	NNODR(-),	SIZMAX(m),	SIZMIN(m),		imesh(-)
1201,	1201,	0.75,	4.5e-3,		2
I_{opt}(A),	BM(T),	rrr(-),	epsilon(-)		
20.0d3,	2.0,	100.0,	-0.3d-2		
ac(m^2),	ah(m^2) ,	pst(m),	dh(m),	acu(m^2),	
1.72d-4,	1.114d-4,	0.735,	6.96d-4,	1 .4988736d-4,	
asc(m^2),	ajk(m^2),	pjk(m)			
2.20428d-5,	1.79d-4,	0.06992			
dyt(s)	detime(s),	Pin(pa),		Pout(pa),	Tin(pa)
1.0,	4.56,	5.0675e5,		3.0405e5,	5.0

L.Dresner analyzed the minimum quench energy for the single superconducting strand in the adiabatic condition subjected a pot disturbance. The minimum quench energy is written as follows[3]

$$MQE = \frac{\pi(\gamma C)A\sqrt{k}\left(T_C - T_{opt}\right)^{1.5}\left(1 - I_{opt}/I_C\right)}{\left(I_C/A_{Cu}\right)\sqrt{\rho_{stab}}\sqrt{I_{opt}/I_C}}\left(\frac{T_{CS}}{T_{opt}}\right)^{1.5} \quad (5)$$

where all the parameters are calculated on the solids code in the Gandalf for 5 K operating temperature.

Fig.9 plots the minimum quench energy versus the Cu/SC ratio for the 360 strands. It includes the NbTi superconducting strand and the pure strands. The current distribution in the all over the strands is uniform. For the lower operating parameters, the higher Cu/SC has advantage.

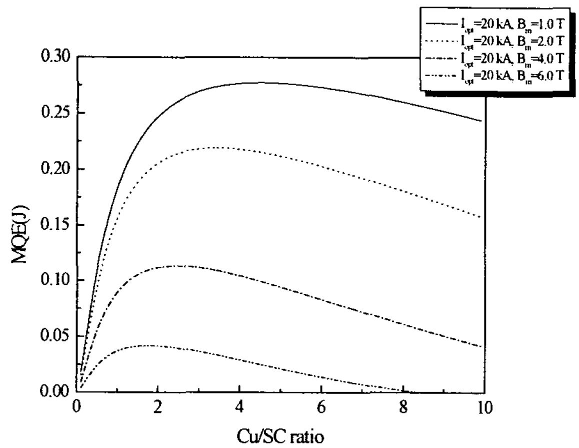

Fig.9 Minimum quench energy of 360 strands with each strand diameter of 0.78 mm versus Cu/SC in various fields with J_{opt} =349.0 A/mm^2, for the adiabatic condition subjected pot disturbance, the current uniform distribution among strands.

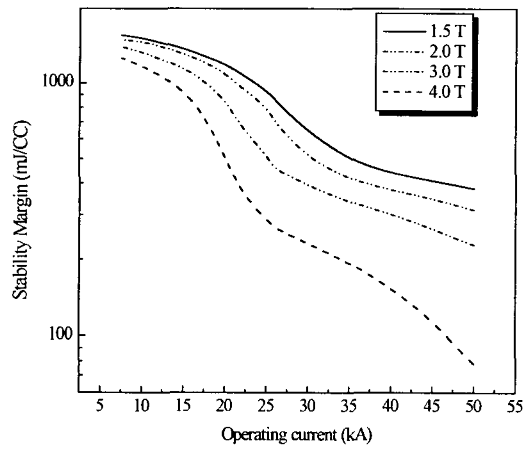

Fig.10 Stability margin versus operating current for various Cu/SC ratio and superconducting strands in CICC, based on ZERODEE code simulation results.

Based on the zero-dimensional model, the stability margin of CICC is simulated. The code is ZERODEE which was developed by the Crydata[6].

The results of J.Miller have shown that additional copper strands are not efficient in the initial current sharing to decrease the Joule heating and thus displace the power balance[4]. Therefore, L.Bottura postulated that the co-wound stabilizer strands (pure copper strands) should be neglected for the stability design[5]. We present a simulation result, i.e. the pure copper strands included. In the simulation, steady stat heat transfer coefficient between the supercritical helium and strands is 600 W/m^2-K which is from the KSTAR design criteria. The stability margin versus operating current is shown in the Fig.10 for various current in Cu/SC = 2.8.

V. CONCLUSION

Based on the simulation, the influence of the Cu/SC ratio in the NbTi superconducting strands and number of NbTi strands on all the parameters for case-1 and case-2 are weakly.

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