A Design Study of Stable Coil Current Control Method for Back-to-Back Thyristor Converter in JT-60SA

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(Received: 30 October 2009 / Accepted: 17 January 2010)

This paper describes the stable coil current control method of back-to-back thyristor converters in parallel connection as a design study. The back-to-back thyristor converter is applied to "Base PS" which is low-voltage power supply for PF coil in JT-60SA. This converter has six arms of anti-parallel connected thyristor devices to enable to operate with 4 quadrant operation. In principle, the dead beat control method is applied on the current feedback control algorithm. In addition, the non-interacting control method is adopted between coil current and circulating current among converters, which is necessary for smooth reversing of the coil current polarity. The rate limiter for control angles of thyristor converter is introduced to suppress the excessive current unbalance between converters. To estimate the proposed coil current control method, the "Base PS" model is simulated by "PSCAD/EMTDC" code. From the simulation results, the stable control capability was obtained.

Keywords: JT-60SA, Power supply for poroidal field coil, Back-to-Back thyristor converter, Coil current control, Rate limiter, PSCAD/EMTDC

1. Introduction

JT-60SA project is that European Union (EU) and Japan collaborate in order to contribute to the early realization of fusion energy by supporting ITER (International Thermonuclear Experimental Reactor) project. As the main mission of JT-60SA machine, complementary experiments for ITER are planned to aim at long-pulse operation (plasma flattop period of 100s) with high β plasma [1,2]. In comparison with JT-60U machine, superconducting toroidal magnetic field (TF) coils and poloidal magnetic field (PF) coils are applied on JT-60SA to achieve steady-state plasma operation. The PF coils are composed of 4 units of CS (Center Solenoid) and 6 units of EF (Equilibrium Field) coil to control plasma shape. Therefore, 10 units of magnet power supplies for each PF coil are necessary to control plasma.

The magnet power supplies for PF coils can control coil current using low voltage during steady-state operation such as plasma flattop region because PF coils are superconducting coils without resistance. For this reason, the magnet power supply consists of a low voltage power supply called to "Base PS" and a high voltage power supply. The high voltage power supply is only activated during plasma initiation and plasma current ramp-up. In other period of plasma operation, only "Base PS" controls coil current with conditions of no plasma perturbation, etc.

In the "Base PS", presently existing converter transformers of JT-60U are planned to be reused from the view point of effective utilization of equipments of JT-60U and cost effectiveness. Corresponding to their transformers, the "Base PS" consists of 2 or 4 units of thyristor converters in parallel. The thyristor converter to be used in the "Base PS" shall be back-to-back thyristor converter, in which six arms have anti-parallel connected thyristor devices to enable to operate with 4 quadrant operation. This solution is planned to be applied to magnet power supply for PF coils in ITER [3]. As the merit of back-to-back converter, the i^2t quantity of converter transformer could be rationalized for bi-directional current application in comparison with a standard three-phase bridge converter for unidirectional current application. On the other hand, as the demerit of this solution, an excessively large current may appear when unexpected short circuit was made by miss firing of the gate control. In particular, double ON state of thyristor devices connected anti-parallel in a same arm must be avoided absolutely.

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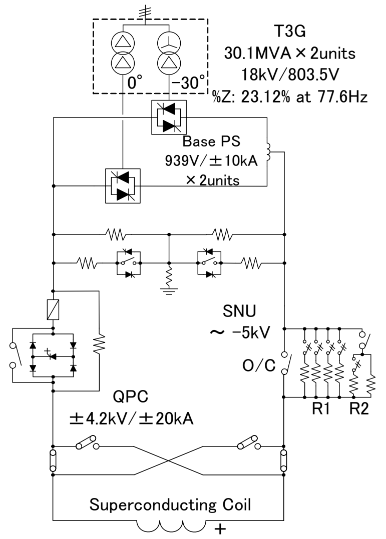
With the control of the "Base PS", rapid control response is required as fast as possible for feedback control of plasma current and shape in Tokamak type fusion experiment devices including JT-60SA. However, current unbalance between converters connected in parallel with phase shifted transformers might be serious problem when fast changing of control angle was required. In the worst case, over-current caused by the unbalance may terminate the plasma operation.

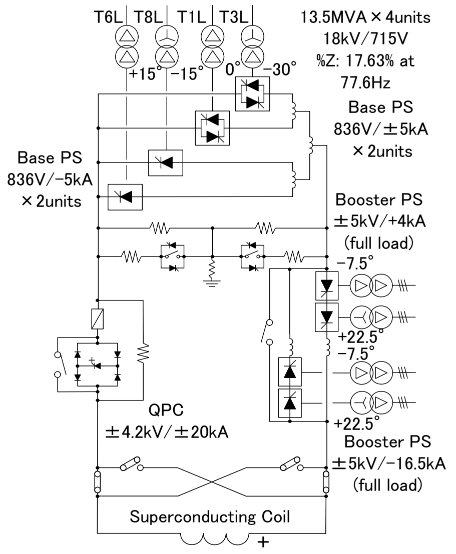
This paper describes the stable coil current control method of back-to-back thyristor converters as a design study. Moreover, to estimate the proposed coil current control method, the "Base PS" model is simulated by "PSCAD/EMTDC" code [4].

2. Circuit configuration of PF coil power supply

Typical circuit configurations of PF coil power supply (PS) are shown in Fig. 1.



(a) CS1



(b) EF2

Fig. 1 Typical circuit configuration of PF coil PS.

The PF coil PS consists of the "Base PS" with back-to back thyristor converters and the "Booster PS" or "Switching Network Unit (SNU)" in series. Basically, the rating of "Base PS" is about ±1 kV/±20 kA, though the output voltage value depends on the reused transformers in JT-60U. The "Booster PS" reuses present vertical field coil power supply in JT-60U to suppress production cost. The "SNU" can apply high voltage on the PF coils by commutating circuit current to the resistance. The both of them can apply a maximum of 5 kV on the PF coils. In addition, the "Quench Protection Circuit (QPC)" is connected to the PF coil in series. The "QPC" has the function of fast extraction of the stored magnetic energy of a superconducting coil to protect a superconducting coil in the case of coil quench [5].

The PF coil PS must control bidirectional coil current for plasma operation. Therefore, the circulating current control in the "Base PS" is adopted to change the polarity of current smoothly.

3. Proposed coil current control method of back-to-back thyristor converters in JT-60SA

3.1 Converter operation mode

The "Base PS" consists of 2 or 4 units of back-to-back thyristor converters in parallel. The rated currents of each thyristor converter are 10 kA with 2 units and 5 kA with 4 units, respectively. To control the desired coil current, activated converters must be chosen corresponding to coil current value. In this paper, the control method for the "Base PS" with 2 units is only described because the control method of both of 2 and 4 units are almost the same.

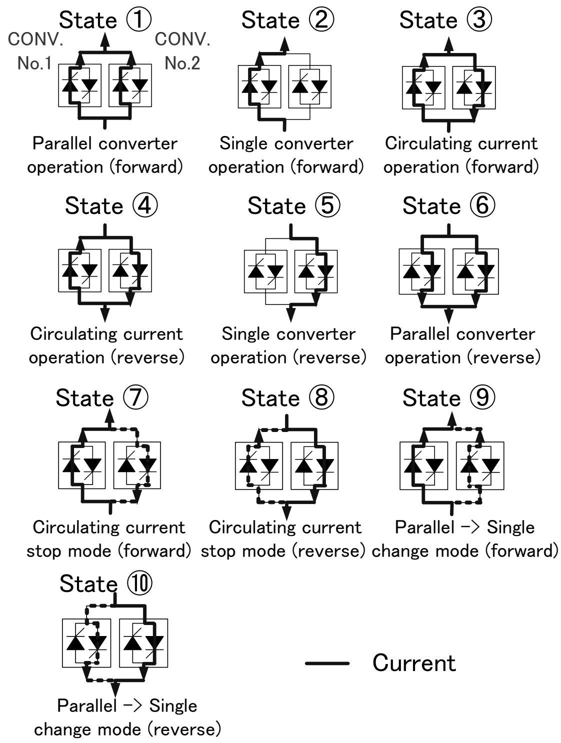


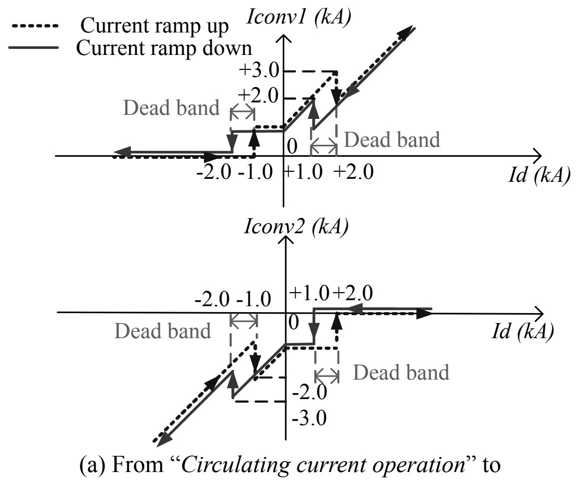
Fig. 2 Converter operation modes.

Since a unit of back-to-back thyistor converter has three operation states (positive/negative current operation, suspended mode), the combination of parallel connected converters allow us a lot of operational flexibilities. However, as shown in Fig. 2, six converter operation modes (State No.1 - No.6) and four converter operation transition modes (State No.7 - No.10) can control coil current considering the simplicity of calculation algorithm, because it is enough to cope with the expected operation region of the coil current. Main operation modes of back-to-back thyristor converters are "*Parallel converter operation*", "*Single converter operation*", and "*Circulating current operation*".

3.2 Threshold level in transition of converter operation mode

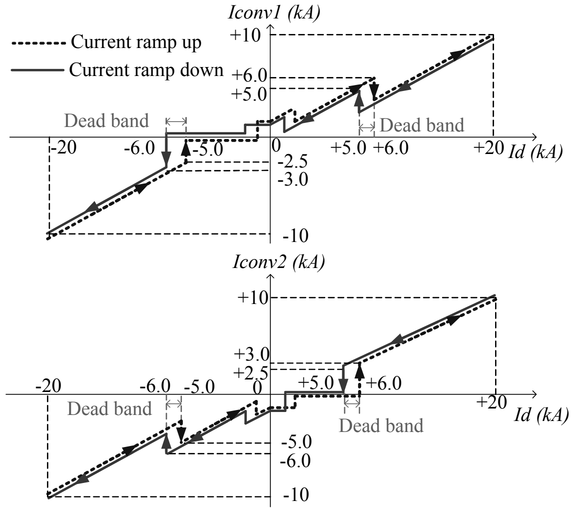
Each converter operation modes as shown in Fig. 2 are switched corresponding to coil current. The proposed coil current control method has a dead band in two thresholds level for transition of converter operation mode. For the dead band, stable coil current control near threshold can be achieved even if coil current changes across the threshold level many times. The transition from "*Circulating current operation*" to "*Single converter operation*" is shown in Fig. 3 (a). The transition from "*Single converter operation*" to "*Parallel converter operation*" is shown in Fig. 3 (b). "*Iconv1*" and "*Iconv2*" correspond to converter output currents of CONV. No.1 and No.2 as shown in Fig. 2. "*Id*" corresponds to coil current. The threshold levels in the case of current ramp-up are -5 kA, -1 kA, +2 kA, and +6 kA. On the other hand, the threshold levels in the case of current ramp-down are -6 kA, -2 kA, +1 kA, and +5 kA.

The state transition diagram in the proposed control method is shown in Fig. 4. The converter operation mode is chosen in operational conditions (State No.1 – No.10) as shown in Fig. 2 corresponding to coil current and converter output current.



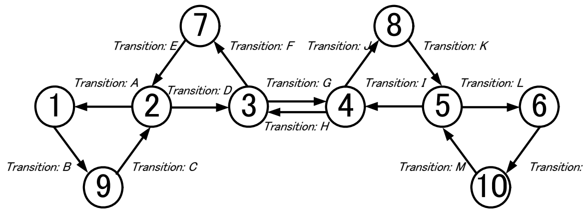
(a) From "*Circulating current operation*" to "*Single converter operation*"

Fig. 3 Transition of converter operation mode.



(b) From "*Single converter operation*" to "*Parallel converter operation*"

Fig. 3 Transition of converter operation mode (Continue).



Note: 1 ~ 10 indicate "*state*" of converter operation mode as shown in Fig.2.

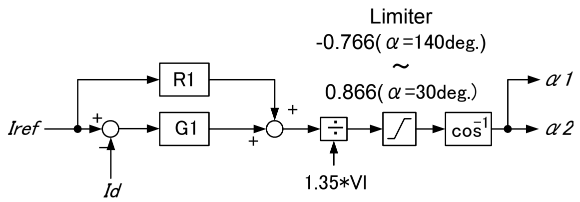
	Criteria
Transition: A	*Id* > +6.0 kA
Transition: B	*Id* < +5.0 kA
Transition: C	*ABS(Iconv2)* ≦ +0.2 kA
Transition: D	*Id* < 1.0 kA
Transition: F	*ABS(Iconv2)* ≦ +0.2 kA
Transition: E	*Id* > +2.0 kA
Transition: G	*Id* < 0.0 kA
Transition: H	*Id* ≧ 0.0 kA
Transition: I	*Id* > −1.0 kA
Transition: J	*Id* < −2.0 kA
Transition: K	*ABS(Iconv1)* ≦ +0.2 kA
Transition: L	*Id* < −6.0 kA
Transition: M	*ABS(Iconv1)* ≦ +0.2 kA
Transition: N	*Id* > −5.0 kA

Fig. 4 State transition diagram.

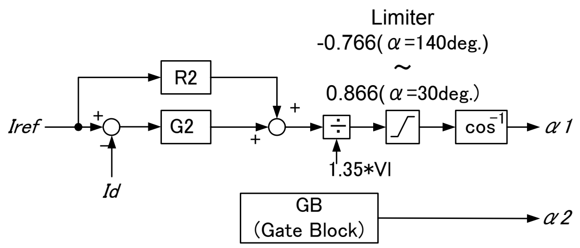
3.3 Coil current control

In the coil current control of the "Base PS", a deadbeat control method is applied on the current feedback control algorithm to achieve rapid control response of coil current for plasma current and shape. This method is one of the discrete digital control methods using z transformation and has a merit that a controlled variable can be corresponded with a reference value per a sampling time. In addition, with circulating current operation, the non-interacting control method is adopted between coil current and circulating current among converters, which is necessary for smooth reversing of the coil current polarity [6].

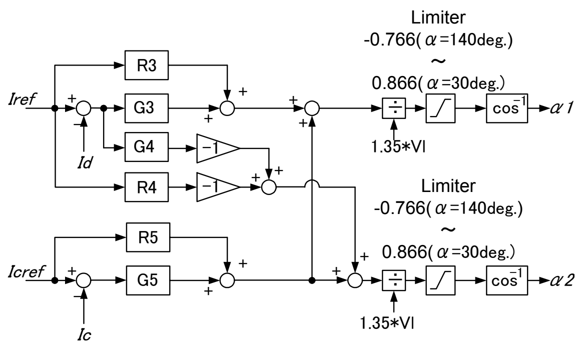
Figure 5 shows the control block diagrams for coil current corresponding to each converter operation mode. The available range for control angle of converters is from 30 degrees to 140 degrees. The circulating current is defined as the constant value of +1 kA with circulating current operation. In Fig. 5 (a), the same control angle is applied to the two converters connected in parallel. In Fig. 5 (b), the suspended converter has "Gate Block (GB) mode" to stop providing gate pulses to converter.



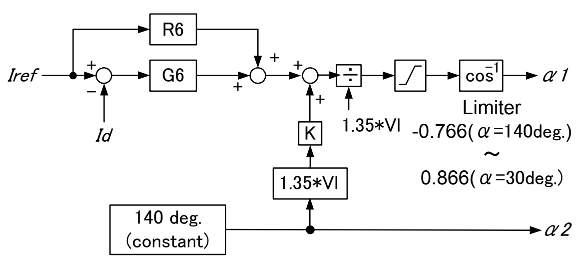
(a) Parallel converter operation



(b) Single converter operation

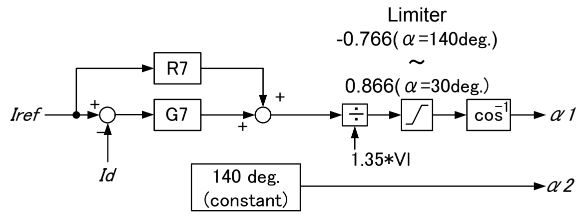


(c) Circulating current operation



(d) Circulating current stop mode

Fig. 5 Control block diagrams for coil current (for positive coil current).



(e) Parallel ->Single change mode

Notes:
Iref: Reference current (kA)
Id: Coil current (kA)
Icref: Reference circulating current (=1kA)
Ic: Circulating current (kA)
G1: Gain (=300.0)
G2: Gain (= 300.0)
G3: Gain (= 300.0)
G4: Gain (=298.5)
G5: Gain (=0.5)
G6: Gain (= 150.0)
G7: Gain (= 150.0)
R1: Circuit resistance including AC side (=2.742mΩ)
R2: Circuit resistance including AC side (= 5.484mΩ)
R3: Circuit resistance including AC side (= 5.484mΩ)
R4: Coil resistance (= 0.0 mΩ)
R5: Circuit resistance including AC side (= 5.484mΩ)
R6: Circuit resistance including AC side (= 5.484mΩ)
R7: Circuit resistance including AC side (= 5.484mΩ)
K: Adjust gain (K=Ic / (0.1 20kA))*
Vl: Secondary winding voltage (=0.8035kV)
α1: control angle for Conv1
α2: control angle for Conv2

Fig. 5 Control block diagrams for coil current (for positive coil current). (Continue)

4. Simulation to estimate the proposed control method

To estimate the proposed control method, the "Base PS" model is simulated by "PSCAD/EMTDC" code. The simulation model is shown in Fig. 6. The circuit parameters of this model are presented in Table 1.

Table 1 Parameters of the simulation model

Components	Parameters	Values
Converter	ON resistance	250 μΩ / 1 arm
	Forward drop voltage	2.5 V / 1 arm
	Inter-phase inductor	500 μH / 1 unit
	Units	2
Transformer	Capacity	30.1MVA
	Winding voltage	18 kV / 803.5 V
	%Z	22.74% at 77.6Hz
	Winding type	Dd, Yd
	Units	2
Coil	Inductance	0.3 H
DC Feeder	Resistance, Inductance	1.35 mΩ, 588.3 μH
AC Feeder	Resistance, Inductance	3.866 mΩ, 280.2 μH
AC power source	Voltage, Frequency	18 kV, 77.6Hz

The coil inductance is 0.3 H which is nearly equal to the inductance of CS in JT-60SA. The inter-phase inductor value for converter is 500 μH to suppress unbalance current among converters within 10% of rated converter output current in parallel converter operation. In this simulation, the "Booster PS" and "SNU" are removed from the circuit to estimate only control capability of the "Base

PS".

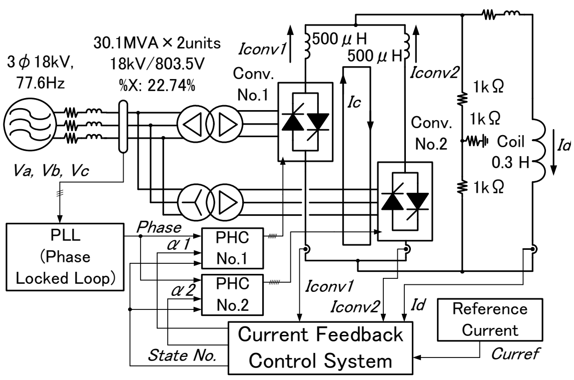
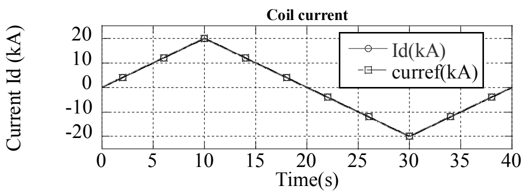
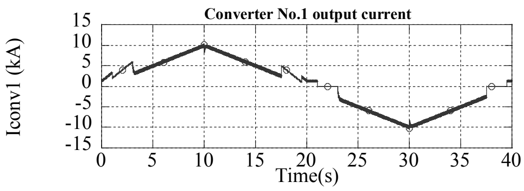


Fig. 6 Simulation model.

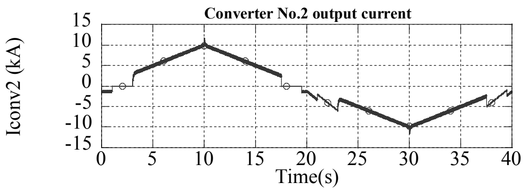
The simulation results of the "Base PS" are shown in Fig. 7. In this case, coil current reference is changed between -20 kA and +20 kA. From the results, the "Base PS" can control coil current corresponding to reference as shown in Fig. 7 (a). Moreover, in Fig. 7 (d), the expected transition of converter operation mode is observed corresponding to coil current values.



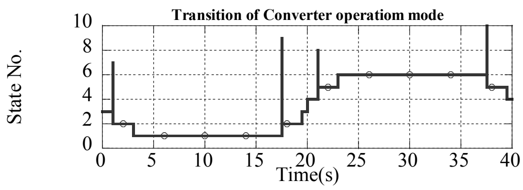
(a) Coil current "*Id*" and reference "*curref*"



(b) Converter No.1 output current "*Iconv1*"



(c) Converter No.2 output current "*Iconv2*"

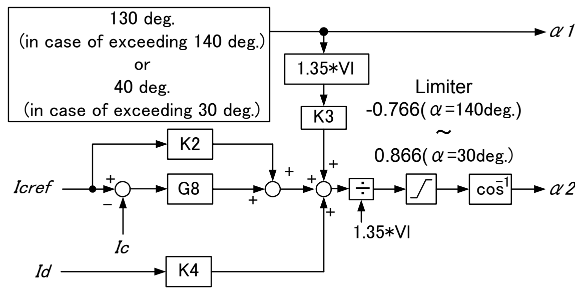


(d) Transition of converter operation mode

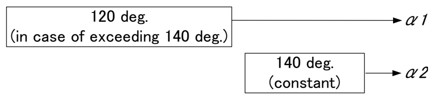
Fig. 7 Basic operation in the "Base PS".

5. Step response

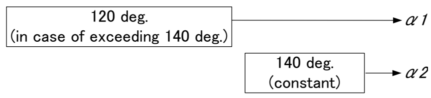
To estimate control response in the "Base PS", a step response is simulated by the "Base PS" model indicated in the chapter 4. In the step response, the control block diagrams as shown in Fig. 5 are saturated because control angles for converters exceed between 30 degrees and 140 degrees. In particular, during "*Circulating current operation* (State No.3 or No.4) " and "*Converter operation transition mode* (State No.7 or No.8 or No.9 or No.10)", the "Base PS" may causes over-current among converters. To avoid abnormal state such as over-current, control angles for converters are calculated by the control block diagrams as shown in Fig. 8 during saturated region. Figure 8 shows the control block diagrams in "*Circulating current operation*" and "*Converter operation transition mode*" in the case of positive coil current.



(a) Circulating current operation



(b) Circulating current stop mode



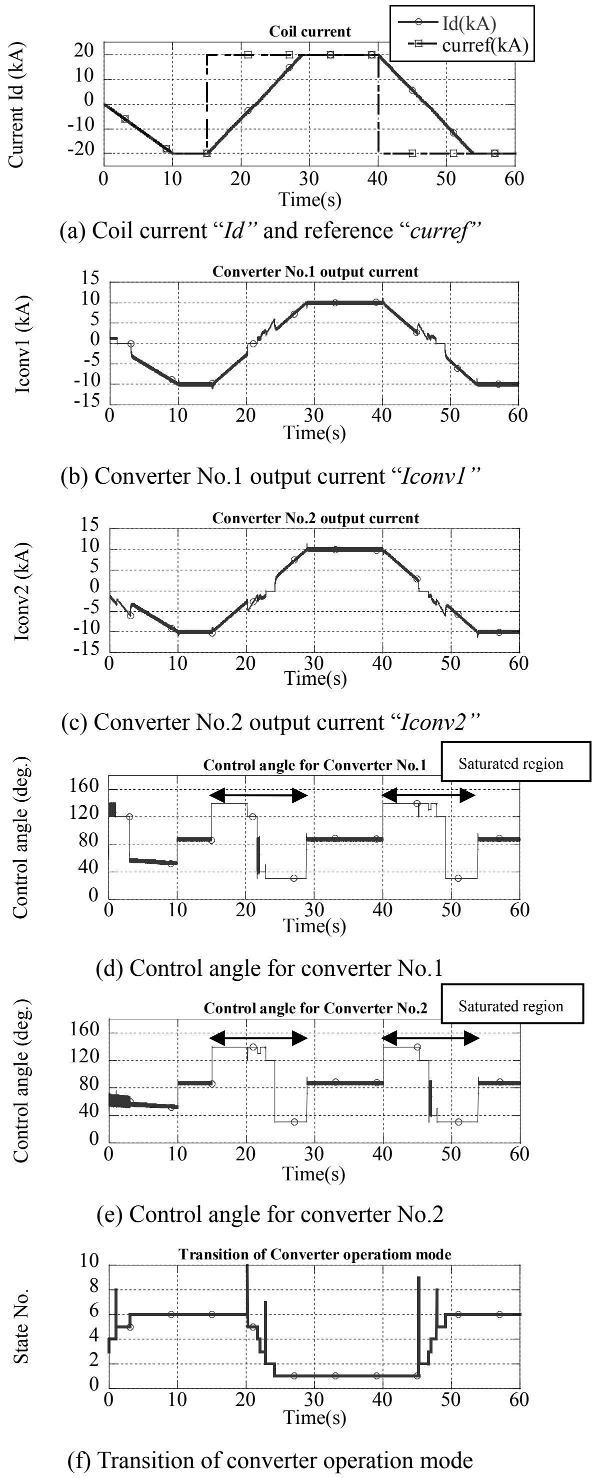
(c) Parallel ->Signal change mode

Notes:
Icref: Reference circulating current (=1kA)
Id: Coil current (kA)
Ic: Circulating current (kA)
G8: Gain (= 1.5)
K2: Adjust gain (= 1.096e−2)
K3: Adjust gain (= −0.998)
K4: Adjust gain (= 5.474e−2)
Vl: Secondary winding voltage of Trans.(= 0.8035kV)
α1: Control angle for Conv. No.1
α2: Control angle for Conv. No.2

Fig. 8 Control Block diagrams for coil current during a saturated region (for positive coil current).

In Fig. 8 (a), the "Base PS" controls the only circulating current using the sub converter (CONV. No.2) because the main converter (CONV. No.1) to control coil current is saturated. Moreover, a control angle for main converter during saturated region is shifted to 40 degrees or 130 degrees to avoid exceeding the available range of control angles in both of main/sub converters.

The simulation results of step response in the "Base PS" are shown in Fig. 9. In this case, the reference changes rapidly from -20 kA to +20 kA at t=15s and from +20 kA to -20 kA at t=40s. From the results, stable coil current control during saturated region is observed without abnormal state such as over-current.



(a) Coil current "*Id*" and reference "*curref*"

(b) Converter No.1 output current "*Iconv1*"

(c) Converter No.2 output current "*Iconv2*"

(d) Control angle for converter No.1

(e) Control angle for converter No.2

(f) Transition of converter operation mode

Fig. 9 Step response simulation.

6. Effect of rate limiter for control angle

In "*Parallel converter operation*", unbalance current between converters appeared by fast changing of control angle. As an example, the converter output current during "*Parallel converter operation*" in Fig. 7 is shown in Fig. 10. To suppress unbalance current in parallel converter operation, the rate limiter for control angle is applied to the control algorithm. In this simulation, with all converter operation modes, the maximum rate of rate limiter is fixed at 18000 deg./s which corresponds to the maximum change rate of phase in cosine curve of 50 Hz. The simulation result is shown in Fig. 11. As a result, unbalance current can be suppressed satisfactorily by using the rate limiter for control angle.

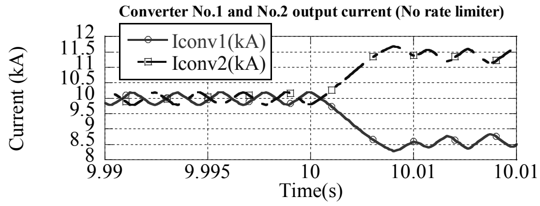


Fig. 10 Converter output currents without rate limiter.

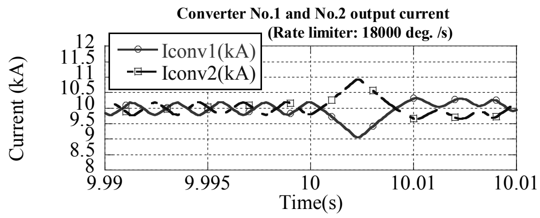


Fig. 11 Converter output currents with rate limiter.

7. Summary

The stable coil current control method of the "Base PS" with back-to-back thyristor converters in parallel connection was proposed as design study of JT-60SA. The proposed control method has the following features;

(a) Six converter operation modes

(b) The thresholds with a dead band in transition of converter operation modes

(c) Dead beat control method for coil current

(d) Non-interacting control method between coil current and circulating current

(e) Rate limiter for control angles to suppress unbalance current among converters.

To estimate the proposed control method, the "Base PS" model is simulated by "PSCAD/EMTDC" code. As the simulation results, the stable control capability was obtained.

Acknowledgements

This work was supported within the framework of the "Broader Approach Internationals Agreement".

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