Analysis of AC Power System for JT-60SA Superconducting Magnets

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- Main magnets are super conducting for long operation (~ 180 s)
- 10 Poloidal filed coils (4 CS, 6 EF coils)
- 18 Toroidal field coils (2.25 T @ center of plasma, stored energy 1 GJ)
Drastic current change around plasma ignition and ramp-up

Current waveforms in the operation

CSs induce current in plasma for heating and confinement
EF coils control shape and position of plasma
High voltage (< 5 kV) is necessary only at ignition and ramp-up phase.
Circuit Configuration for PF magnets

High voltage converter needs large reactive power

for CS, EF3,4

- RI = LdI/dt
- SNU (switching network unit), -5 kV
- Base PS ±1 kV, ±20 kA
- QPC (quench protection circuit)
- Resister is inserted for induction and initiation of plasma
- The resistor is bypassed at 5 s after the ignition

for EF1,2,5,6

- Booster PS ±5 kV, +4 kA -14.5 kA
- Base PS ±1 kV, +10 kA -20 kA
- Booster PS is used for highspeed control of plasma shaping
- Low voltage operation of Booster PS cause large reactive power
Dedicated motor-generator for PF Magnets

250 MVA is required for PF magnets power supplies in total

Output Power | 400 MVA
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Voltage | 18,000 V
Current | 12,830 A
Power Factor | 0.62
Rotation | 582~406.5 rpm
Frequency | 77.6~54.2 Hz
Discharge Energy | 2.650 GJ

Issues

- Over voltage due to breaking large power
- Harmonic current (heating in damper winding)
Issue 1. Over voltage due to magnet quench

All PF circuits start fast discharge even when only one magnet quench disconnected

- Inverse time characteristics
- Definite time characteristics

• Crowbar (thyristor and mechanical hybrid) breaks load in a moment (~ ms)
• Voltage controller of H-MG can not suppress the rapid change
• Power reduction is only way to reduce the over voltage
Issue 2. Harmonics due to reactive power reduction

“Asymmetric control” reduces reactive power of series converters

How to split Vdc

\[ P = 1.35 \times V_{ac} \times I_{DC} \cos(\alpha) \]
\[ Q = 1.35 \times V_{ac} \times I_{DC} \sin(\alpha) \]
\[ V_{DC} = 1.35 \times V_{ac} \times \cos(\alpha) \]

Current in primary side

- Vdc is proportional to active power P and reactive power Q
- Reactive power can be reduced by changing distribution of Vdc
- Criteria of harmonics is \( I_{eq2} = \sqrt{\sum \frac{N^2}{2} \times I_N^2} < 15\% \) of nominal current
How to reduce harmonic current

Difference power supplies cancel harmonics together

• This assumption depends on command phase angles and amplitude of current for each converters during discharge
• The effect should be confirmed by integrated model of PS system
Integration model

All components are implemented without simplification in simulink

Voltage controller (AVR)

Thyrister converters

Mutual coupling of magnets

Phase shift transformers

Booster PS type × 4 (EF1-4)
Pass criteria $+6\% < +18\%$ (definite time)

**Overvoltage estimation at quench**

- **Large reactive power reduction**
- **Active power is negligible comparing to reactive power**

Graphs showing:
- $I_{coil}$ in [kA]
- $H$-MG voltage in [pu]
- Reactive Power in [MVar]
- Active Power in [MW]

Legend:
- **w/o asymmetric control**
- **w/ asymmetric control**

1.06 pu settle time 0.2 $<<<<100$ s
Harmonic current estimation

$I_{2eq} = 5.96\% \ll 15\% \ @ \ t = 0.1\ s \ (around \ ignition)$

Fundamental (71.7Hz) = 9518, THD=5.00\% \ @ \ t = 0.1\ s

Fundamental (71.7Hz) = 8915, THD=6.04\% \ @ \ t = 0.1\ s
Harmonic current estimation

\[ I_2eq = 3.51 \% \ll 15\% \text{ at } t = 4.9 \text{ s (just before Booster PS stop)} \]

Fundamental (72.2Hz) = 9159, THD= 4.26\% \text{ at } t = 4.9 \text{ s}
Fundamental (72.2Hz) = 7411, THD= 5.48\% \text{ at } t = 4.9 \text{ s}
Conclusion

- Large reactive power is required for PF magnet system in JT-60SA
- At magnet quench, over voltage of H-MG is happened due to load breaking
- Asymmetric control can reduce reactive power
- However, asymmetric control causes harmonic current
- In JT-60SA, phase shift transformer is optimized for reduction of harmonics
- Series connected converters for each magnet can reduce the harmonics together
- Over voltage and harmonic current is estimated using integration model of PS system
- Over voltage is suppressed less than 6 % (criteria $< 18 \%$)
- Harmonic current is also suppressed less than 6 % (criteria $< 15 \%$)