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Research of Active Regulation for High-Stability Flat-Top Pulsed High Magnetic Field

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I. Introduction

Pulse generator, with advantages of large energy storage and flexible control, is an ideal power supply for flat-top magnetic field. During discharge progress, the kinetic energy of flywheel is decreased with energy releasing that the output voltage of pulse generator is decreased as well as frequency. Furthermore, due to characteristics of nonlinearity and time variant, the accurate model of pulse generator is hardly to be established. The ripple improvement by the optimization of control strategy for power supply is limited by the problems of pulse generator itself. The ripple amplitude is small enough at the flat-top that a high stability flat-top magnetic field can be achieved by dozens of compensating ampere from an active regulator]. Compared with tens of thousands amperes form pulse generator, an active regulator can reduce the system inertia and increase the system response which are helpful for realizing high stability flat-top magnetic field. On the base of achieved active regulation system for high stability flat-top magnetic field powered by battery banks, a scheme of active regulation for pulse generator is proposed to reduce the flat-top ripple to 100 ppm in this paper.

II. Operation Principle of Flat-top Field System

At Wuhan National High Magnetic Field Center (WHMFC), the power supply is a 100 MW / 100 MJ pulse generator with two 67.5 MW 12-pulse thyristor rectifier system. The out-put voltage of pulse generator is 6.9kV, and excitation adjustment is abandoned for its slow electromagnetic process relative to flat-top. Two 12-pulse rectifiers powers the outer coil and inner coil of the daul-coil magnet respectively.

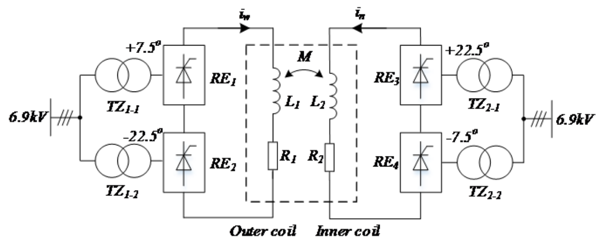


Fig. 1. Schematics of flat-top magnetic field system.

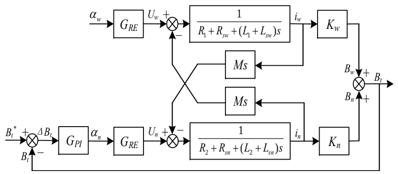


Fig. 2. Control loop of the flat-top magnetic field powered by pulse generator.

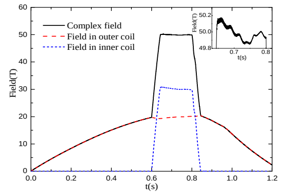


Fig. 3. Flat-top magnetic field by PI feedback control

III. Design of Active Regulator

A. Circuit Topology

The active regulator applied in flat-top magnetic field has the particularity of high output voltage and high frequency output current. Cascade H-bridge inverter with a LCL filter is proposed as the topology of active regulator

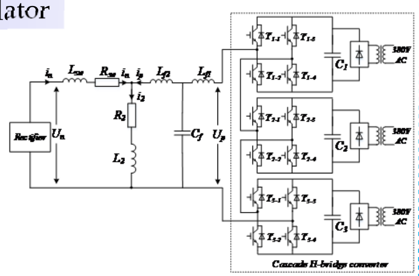


Fig. 4. Circuit topology of active regulator

Fig. 5. Photos of facilities and prototype of inverters of active regulator. (a) Pulse generator. (b) Rectifiers. (c)Single H-bridge inverter. (d) Cascade H-bridge inverters.

B. Circuit Calculation

The equation shows the relationship of switching frequency f_s, tracking error range δ, filter inductance L_p and DC link voltage U_{dc}. The switching frequency f_s of active regulator is inversely proportional to the product $\delta{\cdot}L_p$ of tracking error range and inductance, and is proportional to the DC link voltage U_{dc}

$$f_s=\frac{1}{T}=\frac{1}{T_{on}+T_{off}}=\frac{U_{dc}^2-U_2^2}{4\delta L_p U_{dc}}$$

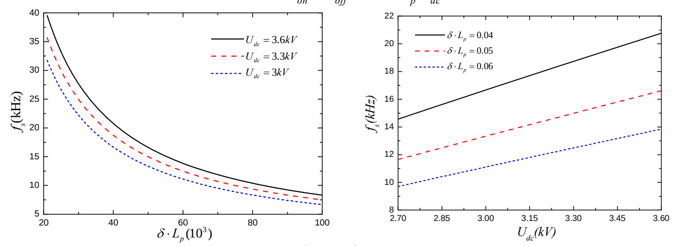


Fig.6. (a) Relationship between f_s and $\delta{\cdot}L_p$ with constant U_{dc}. (b) Relationship between f_s and U_{dc} with constant $\delta{\cdot}L_p$.

$$\begin{cases}U_n(t)-L_{sn}\dfrac{di_n}{dt}-R_{sn}i_n=U_p(t)-L_p\dfrac{di_p}{dt}\\ i_2=i_n+i_p\end{cases}$$

Circulating current

$$\begin{cases}i_n=e^{kt}[\int\dfrac{U_n(t)-U_p(t)+L_p\frac{di_2}{dt}}{L_{sn}+L_p}e^{-kt}dt+C_n]\\ i_p=-e^{kt}\{\int[\dfrac{U_n(t)-U_p(t)+L_p\frac{di_2}{dt}}{L_{sn}+L_p}-ki_2]e^{-kt}dt+C_p\}\end{cases}$$

C. Control Strategy Optimization

The active regulator has the same response for the ripple with both high frequency and low frequency that the regulating current has certain coupling with different frequency. The control system of active regulator should be frequency selective to optimize the output characteristics of high frequency and low frequency. On the other hand, two feedback control to the same term has poor robustness relatively that beat control between two control system and unpredictable disturbance is liable to cause control oscillation, which is difficult to the disadvantage to the restraint for circulating current. Therefore, decoupling control should be considered for two power supplies.

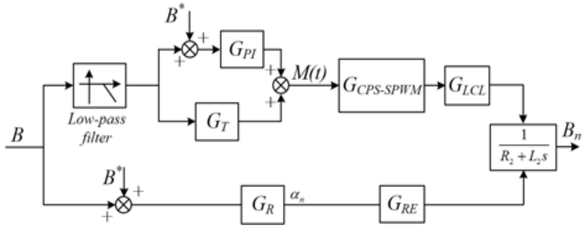
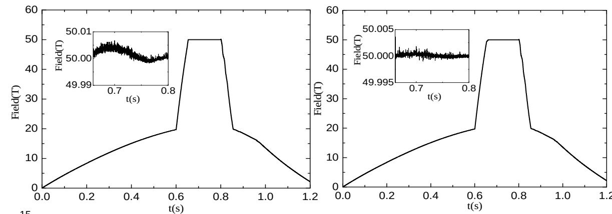
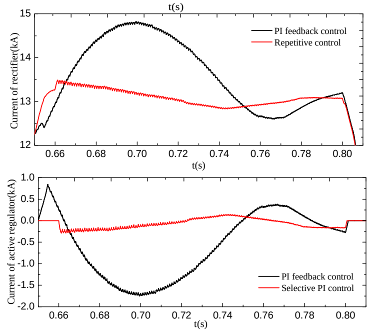


Fig. 7. Structure of optimal control strategy. G_T and G_R are the transfer functions of ripple tracking control and repetitive control respectively.

IV. Simulation Results





High stability flat-top magnetic field is realized by the optimal control strategy. The current comparison indicates that the circulating current between pulse generator and active regulator has been restraint greatly. The current of active regulator has decreased to 300 A, as the red curve.

Fig.8. (a) High stability flat-top magnetic field with active regulator. (b) High stability flat-top magnetic field with active regulator. (c) Current of rectifier with repetitive control. (d) Current of active regulator with selective PI control.

V. Conclusion

This paper proposes an active regulation scheme for high stability flat-top magnetic field generated by pulse generator at WHMFC. According to simulation result, a 50 T flat-top magnetic field with the ripple less than 100 ppm is achieved and the circulating current is controlled at an acceptable level. Prototype of the proposed active regulator is under development and experimental results will be discussed in the spring of 2018.

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