

STUDY OF ENERGY SAVING OPERATION FOR THE TLS BOOSTER POWER SUPPLY

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Abstract

Operating an injector of a synchrotron light source, energy efficiency is an important issue. Dipole and quadrupoles families of the booster synchrotron for Taiwan Light Source (TLS) is resonantly excited by three White circuits at 10 Hz rate. Magnet current cannot response in cycle-by-cycle basic due to resonance nature. The possibility of operation of the booster synchrotron in energy saving mode is explored. Minimizing the duration of magnet excitation without effect of the injected and extracted beam to support top-up operation for the TLS is investigated. Efforts will be presented in this report.

INTRODUCTION

The storage ring of TLS is operated in top-up injection mode at stored beam current 361 mA. Typical beam lifetime is about 6~7 hours, it needs to refill beam at every minute. The booster synchrotron is turned on continually since the top-up injection started from 2005. Energy saving operation of the booster RF system was investigated and activated [1, 2]. The possible operation scenario for the magnets excitation system is studied recently.

There are three families of magnet driven by a White circuit [3, 4, 5, 6, 7]. Each White circuit consists of a DC and an AC power supply in the TLS booster synchrotron. The DC power supply is turned on firstly before AC power supply to protect the polarized electrolyte capacitor. The control sequence is that after DC power supply achieves its nominal value then AC power supply can be enabled. The three families consisted of dipole, focusing quadrupole and defocusing quadrupole magnets. After three families of power supply turned on respectively, the phase regulation algorithm is applied to ensure the relationship between three White circuits to be in phase. The time for turning on DC, AC power supplies and applying phase regulation needs to be ended before beam trigger signal. To proceed the energy-saving of the booster synchrotron, the excitation is removed in reverse order, phase regulation stopped firstly, AC power supply turned off then DC power supply turned off at last. Minimizing the time duration during above cycle will save more electricity.

WHITE CIRCUITS OF THE BOOSTER SYNCHROTRON

There are three families of magnet systems in the booster synchrotron. These are dipole, focusing quadrupole and defocusing quadrupole magnets. Each family includes 12 magnets. The main excitation circuits are configured as three independent White circuits and

resonantly excited at 10 Hz. The White circuit comprises two coupled resonant circuits, which are a bypass capacitor and a DC power supply with two resonant LC circuits. Each White circuit has the same configuration; those AC and DC power supplies work independently. Both DC and AC current are controlled within an error less than 5×10^{-4} . The tune variation during energy ramping should be in the order of 0.01 for stable operation which corresponding to 5×10^{-4} focusing error. This implies that the current of DC and AC components for quadrupole magnets must be stabilized within the same order. The amplitude and phase might be drifted which caused by resonance frequency change slightly due to ambient temperature and heating of the capacitor of White circuit. It takes several hours to achieve thermal equilibrium. The tolerable phase drift was estimated to be 0.1° corresponding to 30 μ sec for 10 Hz normal operation.

The controls system needs to provide adjustable precision for amplitude and phase of 10 Hz sinusoid reference for AC power supplies of three White circuits. The block diagram of White circuit power supplies interface is illustrated in Fig. 1. The White circuit power supply control interface consists of amplitude and phase detector module, high purity 10 Hz generator and amplitude regulator module, digital delay generator (DDG), time to digital converter (TDC), interlock and protection module, 16 bits DAC and ADC module. The amplitude/phase detection module measures the peak of magnet current for the analog PID amplitude regulator of high purity 10 Hz sine-wave generator.

The major function of the White circuit power supply control includes provide 10 Hz reference signal to drive power supply and regulate amplitude and phase of the AC current of magnets [4]. The amplitude regulation loop purpose is to keep magnet current with constant amplitude. The DAC module sets the amplitude reference for the DC/AC power supply, the high purity 10 Hz sine-wave generator module is based on the amplitude reference to generate 10 Hz sine-wave for AC power supplies to control the amplitude of White circuit. Purposes of the phase regulation loop as shown in Fig. 2 is to keep constant phase difference between two quadruple families with dipole.

The operation sequence of the White circuits, three DDG module sets the phase of a 10 Hz trigger signal for three high purity 10 Hz sine-wave generator modules that produces correlated phase of the three 10 Hz sine-wave output. The DCCT device senses the output amplitude of magnet current for the amplitude/phase detection module that directly detects the output phase of magnet current then feedbacks to TDC module for the software, PID phase regulation, to rectify the phase of DDG module.

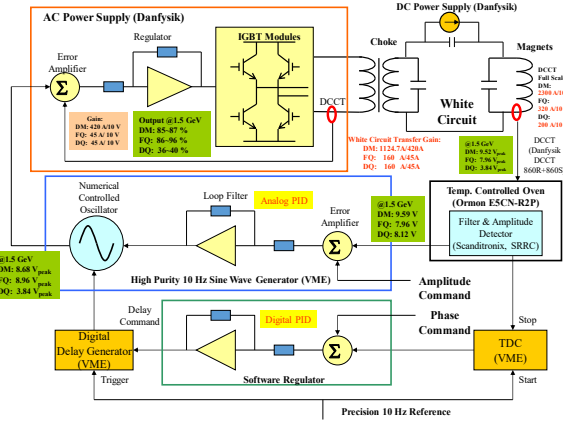


Figure 1: Booster synchrotron AC power supply control interface.

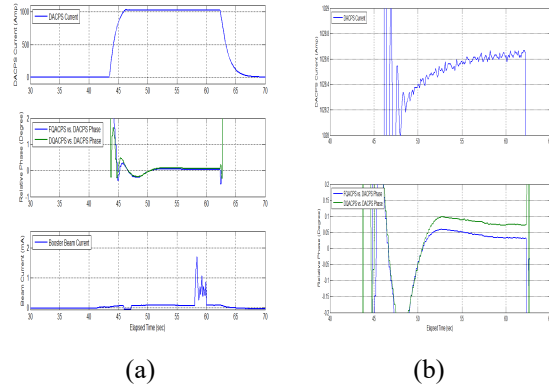


Figure 3: (a) Dipole AC current amplitude (upper), the respective phase difference of FQ/DQ (middle); booster beam current (bottom). (b) Dipole AC current amplitude and phase difference between dipole and FQ/DQ AC current when regulation loop is in action.

SCHEME FOR ENERGY SAVING OPERATION

Excitation of power supplies is applied while injecting beam and removed after to save energy. The beam is injected every minute when top-up mode is activated. It takes about a few injection cycles (10 cycles/sec) to refill to the storage ring. It takes few seconds after nominal value set of the AC/DC power supplies to ensure amplitude and phase tracking stable enough. The time duration required depends on time constant of loads (White circuits), control rules and small resonance frequency drift due to thermal effect. After injection, power supplies are set to zero for save of electricity. In another words, it needs to enable and disable the current output of AC/DC power supplies to operate in energy-saving mode. Operation flow chart is shown in Fig. 4.

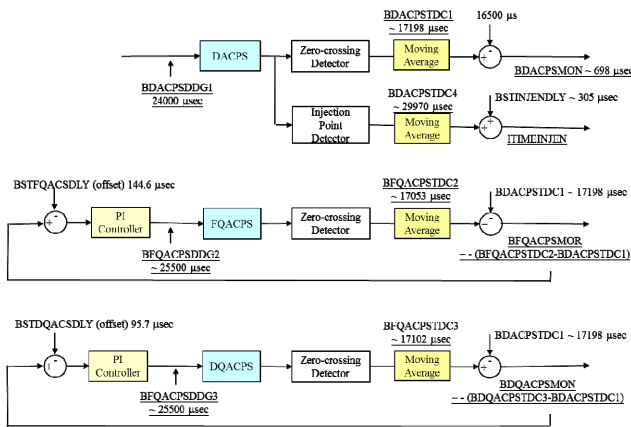


Figure 2: Magnet excitation phasing loops.

In the phase regulation loop, a zero-crossing signals are connected to the time digital converter to measure the zero-crossing timing (phase) of the dipole AC current. The respective zero-crossing timings of the focusing quadrupole (FQ) and defocusing quadrupole (DQ) AC power supply are relative to the dipole current's zero-crossing and are regulated by the phase PI controller that adjusts the phase of 10 Hz driving signal of the FQ and DQ AC power supply. A digital PI regulator is used to keep the phase difference constant between two quadruple families and dipole family. Input of the regulation loop is from TDC and output is to a digital delay generator. Figure 3 (a) shows the amplitude of dipole AC current and the phase difference between FQ/DQ AC current and amplitude and phase regulation loops enabled. Zoom of the amplitude and phase response for this disable/enable operation of power supply is shown in Fig. 3 (b). If the amplitude and phase achieved a certain level the beam can be ramped in booster ring even the amplitude or phase is damped out of the transient response region of PI regulation. The PI regulator minimizes the effect of slow drift to support the working conditions for beam injection and ramping energy in the booster synchrotron. It takes about 10 seconds to regulate the relative phase within 0.1° ($\sim 30 \mu\text{sec}$) and amplitude within 10^{-4} of the nominal current.

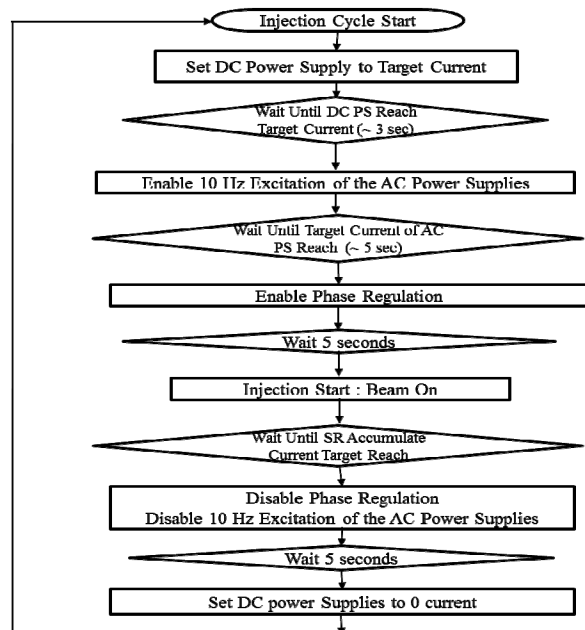


Figure 4: The energy saving operation flow chart.

A preliminary test results for On/Off operation of the White circuits with beam is shown in Fig. 5. After optimizing parameters of the regulation loops, the response time is shortened to the minimum period as shown in Fig. 6. Typical continue running in energy saving mode is shown in Fig. 7.

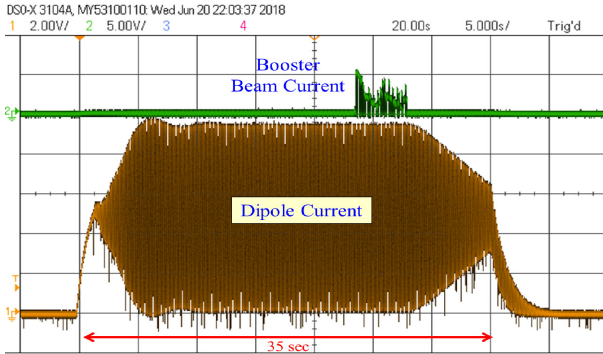


Figure 5: Preliminary test in June for On/Off operation of magnets excitation and booster beam current.

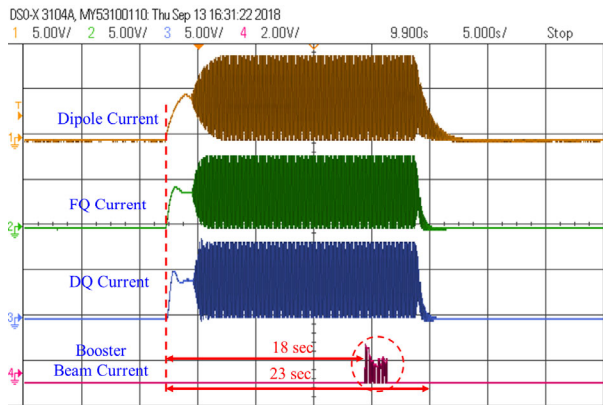


Figure 6: Amplitude and phase regulation loops and beam current after improved in September 2018. All power supplies enabled 18 seconds before beam on for warmup and regulation of amplitude and phase.

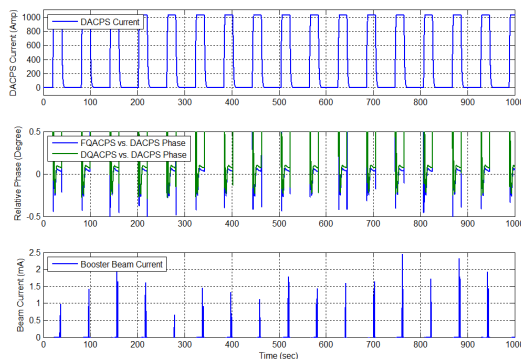


Figure 7: The dipole current, respective FQ/DQ phase difference and booster beam current trend.

Electricity consumption to drive White circuits is 275 kW as shown in Fig. 8. The annually electricity

consumption required for the booster is about 1.5125 MWh (275 kW * 5,500 Hours) which is based on 5,500 hours continuous operation. The power supplies operate with 33% duty cycle to support top-up injection every 60 seconds which is achieved at this moment. Saved electricity is more than 1 MWh annually. Estimated cost saving is more than 70 thousand USD per year based on averaged electricity price USD 0.07/kWh in Taiwan.

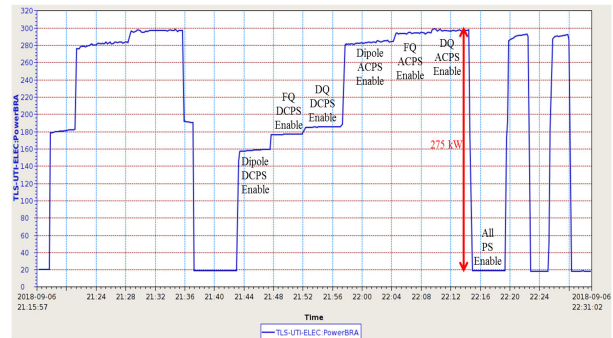


Figure 8: Electricity consumption of the booster main power supplies.

SUMMARY

Energy saving scheme for the booster synchrotron with resonance magnet excitation to support top-up injection for TLS was tested. Further reduce time necessary to reach the conditions for stable beam delivery after power supply enabled need improve response time of the AC power supply amplitude and phase regulation. Various limitation to operate the booster synchrotron in energy saving mode is explored. The magnets excitation can be removed about 40 seconds within a 60-second between consecutive injections. About two-third of the electricity can save in current operation mode without sacrificing its operation performance.

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