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HIGH EFFICIENCY LINEAR POWER SUPPLY WITH A PREREGULATOR CONTROLLED BY KEEPING CONSTANT R_{DS} OF MOSFET

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Abstract

In Synchrotron Radiation Research Center (SRRC) more than ninety linear power supplies with 100 ppm long-term stability are served for correction magnets. To increase the well-known efficiency problem of linear power supply, inside a customer-made bipolar linear power supply a homemade pre-regulator circuitry is in series in front of power stage. By using constant V_{DS} controlled pre-regulator, the power consumption of linear power supply itself could be reduced and the efficiency changes with respect to the output power. On the other hand, with constant R_{DS} controlled pre-regulator, the efficiency is even higher and is the ratio of load resistance and R_{DS}. Design and performance of the pre-regulator circuitry will be demonstrated.

1 INTRODUCTION

Low efficiency is the drawback of linear mode power supply, most of power is dissipated at power device and transformer. A lot of correction magnet power supplies used at Synchrotron Radiation Research Center (SRRC) are linear mode power supplies. The efficiency of power stage of these power supplies is below 50% and it could be lower than 30% if transformer is included.

A pre-regulator in series in front of power stage of linear mode power supply could keep voltage drop on power device a small value and decrease power dissipation such that the efficiency of power supply is increased. There are different types of pre-regulator, for example, SCR type[1]、variable transformer[2]….. In this experiment a programmable HP6032a DC power supply is used as a pre-regulator for linear mode bipolar correction power supply of SRRC. Two kinds of control strategy will be used to control the output of HP6032a and the efficiency of power stage can be figured out both in calculation and measurement. In the final design, VICOR V375A24C600A[3] programmable DC-DC converter is inserted as a pre-regulator controlled by suitable control strategy and the efficiency will be demonstrated.

2 CONTROL STRATEGY

The main goal of pre-regulator is to decrease the voltage drop on power device and keep power device on normal operation, that needs a good control strategy. Conventionally, the parameter to be controlled is the V_{DS} of MOSFET, the output of pre-regulator will change with respect to the output of power supply and keep V_{DS} of MOSFET a constant value; the power device of correction magnet power supply used at SRRC is IRFH6H250 MOSFET, V_{DS} of this MOSFET should be at least 0.6V to let power supply operate normally at maximum 20 amperes output. V_{DS} is decreased when output current of power supply is increased then the output voltage of pre-regulator should increase to keep V_{DS} constant. If output current of power supply is decreased then the output voltage of pre-regulator should also decrease; under this kind of control strategy there is a minimum value of equivalent resistance R_{DS} of MOSFET when output current of power supply is maximum; that is to say, the efficiency of power stage is dependent on output current of power supply.

If the minimum R_{DS} of MOSFET is the parameter of control strategy, the efficiency of power stage is a ratio of R_{DS} and resistance of load and is independent of output current of power supply. Based on above argument, control strategy of keeping constant R_{DS} is better than keeping constant V_{DS}. The efficiency of power stage in series of pre-regulator with these two kind of control strategy will be discussed, one pre-regulator is called constant V_{DS} pre-regulator and the other is constant R_{DS} pre-regulator.

3 EFFICIENCY OF POWER STAGE WITHOUT A PRE-REGULATOR

If the rectified voltage of linear mode power supply is Vdcbus, Rload is the resistance of magnet load and i_D is the output current, then V_{DS} of MOSFET is :

$$V_{DS} = Vdcbus - i_D * Rload$$

Efficiency of power stage is :

$$i_D^2 * Rload / (i_D * Vdcbus)$$

$$\Rightarrow \quad i_D * Rload / Vdcbus \qquad (1)$$

From (1), the relationship between efficiency of power stage and output current is linear, the more output current the more efficiency; the Vdcbus of correction magnet power supply used at SRRC is 24 volts and Rload is 0.4959Ω, then the relationship becomes:

$$i_D * 0.4959\Omega / 24V \qquad (2)$$

Figure 1 is the plot of efficiency versus output current, efficiency is below 50 % within 0 ~ 20 amperes, it shows more than 50 % of energy is dissipated at MOSFET. The difference between equation (2) and figure1 is because the variation of Vdcbus influenced by output current and resistance of transformer.

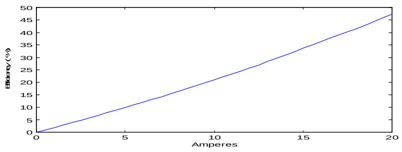
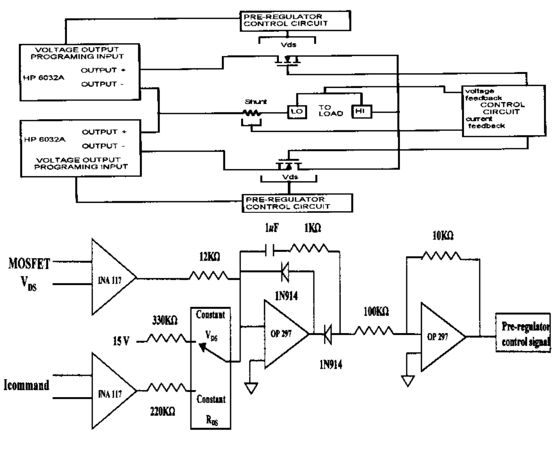


Figure 1

4 EFFICIENCY OF POWER STAGE WITH A PRE-REGULATOR

In the beginning of experiment, there isn't a real pre-regulator in the test setup. HP6032a is an analog programmable power supply, it's function just could be used a pre-regulator and figure 2a is the test setup. The main goal is to know how much efficiency of power stage in series with a pre-regulator controlled by two kind of control strategy could be reached and then to choose a better control strategy, figure 2b is the circuitry of control strategy.



(a)

(b)

Figure 2 (a) test structure setup (b) circuitry of control strategy

4.1 Efficiency of power stage in series with a constant V_{DS} pre-regulator

At this control mode, MOSFET is operated in linear range and the relationship between i_D and v_{DS} is as follow:

$$i_D = K[\,2(v_{GS} - Vt)\, v_{DS} - v_{DS}^2]$$

because v_{DS} is very small, so v_{DS}^2 is neglected,

$$i_D = 2K(v_{GS} - Vt)\, v_{DS} \qquad (3)$$

$$R_{DS} = v_{DS} / i_D = 2K(v_{GS} - Vt) \qquad (4)$$

Equation of efficiency is:

$$i_D^2 * Rload / (i_D * Vdcbus)$$

because $Vdcbus = i_D * Rload + v_{DS}$

so equation of efficiency becomes:

$$i_D^2 * Rload / (i_D^2 * Rload + i_D * v_{DS})$$

$$\Rightarrow \quad i_D * Rload / (i_D * Rload + v_{DS}) \qquad (5)$$

in real design, v_{DS} is set to 0.614 volt, so (5) becomes:

$$i_D*0.4959\Omega/(i_D*0.4959\Omega+0.614V) \qquad (6)$$

Figure 3 is the plot of efficiency versus output current, and it follows equation (6) very well. Benefit gained from a constant V_{DS} pre-regulator is obvious, efficiency of power stage is increased very much.

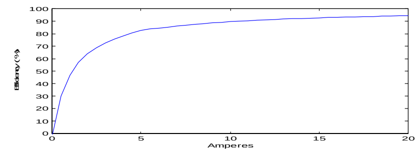


Figure 3

Figure 4 is the plot of variation of v_{DS} within 0 ~ 20 amperes output of power supply, it shows the variation of v_{DS} is very small and the function of control circuit of constant V_{DS} pre-regulator is suitable.

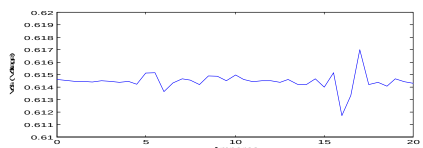


Figure 4

4.2 Efficiency of power stage in series with a constant R_{DS} pre-regulator

Correction magnet power supply used in SRRC is a programmable current mode power supply so that output current i_D is programmed by command $i_{command}$, then

$$i_D \propto i_{command}$$

if v_{DS} is also programmed by $i_{command}$

then $\quad v_{DS} \propto i_{command}$

and $\quad v_{DS} \propto i_D$

let $\quad v_{DS} = R*i_D$

$$R_{DS} = v_{DS} / i_D = R*i_D / i_D = R \qquad (7)$$

Based on the control strategy, R_{DS} could be controlled to be a value as wish no matter what output current is; efficiency could be expressed as follow:

$$i_D^2*Rload / (i_D^2*Rload + i_D^2* R)$$

$$\Rightarrow \quad Rload / (Rload + R) \qquad (8)$$

Under control strategy of constant R_{DS}, efficiency is constant and independent on output current of power supply; the constant value R could be derived from parameter of constant V_{DS} pre-regulator, V_{DS} is set to 0.614 volt so that minimum equivalent R_{DS} is 0.0307Ω (0.614 volt / 20 amperes) and this value is controlled by constant R_{DS} control strategy; efficiency might be calculated as below:

$$0.4959\Omega/(0.4959\Omega + 0.0307\Omega)= 0.942$$

Figure 5 is the plot of efficiency of power stage versus output current of power supply and the efficiency is almost constant.

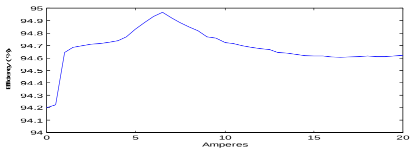
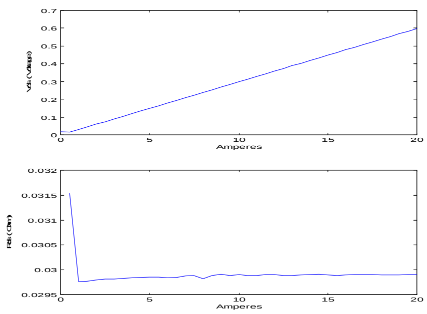


Figure 5

Benefit gained from constant R_{DS} control strategy is more than constant V_{DS} control strategy; figure 6a is the plot of variation of V_{DS} versus output current of power supply, figure 6b is the plot of variation of R_{DS} versus output current of power supply and it is obvious R_{DS} is controlled very well.



(a)

(b)

Figure 6 (a) V_{DS} vs. output current (b) R_{DS} vs. output current

5 EFFICIENCY OF FINAL DESIGN CIRCUIT

Although HP6032a is used as a pre-regulator to test two kind of control strategy circuits and performance of these two circuits are good, but a real pre-regulator is still needed in real application. VICOR V375A24C600A is a compact and high efficiency 600 watts 2.4 ~ 24 volts output programmable DC-DC converter, it is suitable to be used as a pre-regulator. Control circuit used for this module is constant R_{DS} control strategy because more efficiency could be gained. Figure 7 is the final structure of power supply.

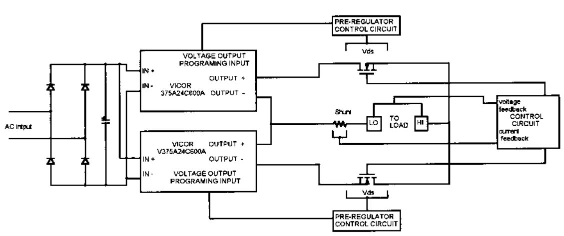


Figure 7

Figure 8 is the plot of efficiency of power stage versus output current of power supply, efficiency is not constant in low output current range because output voltage of VICOR V375A24C600A can not function below 2.4 volts, but normal operation output current of most of correction magnet power supply are larger than 3 amperes so that high efficiency is still gained.

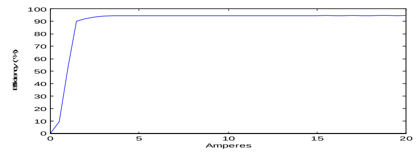


Figure 8

6 CONCLUSION

Efficiency of correction magnet power supply used at SRRC is improved by insertion of a pre-regulator in series in front of power stage, constant R_{DS} control strategy is a better choice for the control of pre-regulator than constant V_{DS} control strategy that could save more power and efficiency is just the ratio of load resistance and R_{DS}. It is not very much suitable for VICOR V375A24C600A to be a pre-regulator because it can't operate below 2.5 volts. But efficiency is higher than 90% in normal operation of correction magnet power supply when output current above 3 amperes.

7 REFERENCES

[1] Operation Manual of BRUKER B-MN 50 / 1500 power supply

[2] Operation Manual of DANFYSIK system 8000 power supply for booster dipole magnet of SRRC

[3] VICOR data sheet: V375A24C600A DC-DC converter