ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THXC07

ADAPTIVE CONTROL OF KLYSTRON OPERATION PARAMETERS FOR ENERGY SAVING AT STORAGE RING OF TPS

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Abstract

To satisfy maximum beam current operation in the storage ring of TPS, the operation parameters of both RF transmitters are set to be able to generate its maximum RF power in daily usage. Under such condition, the klystrons can deliver any power below 300 kW at constant AC power consumption which is about 520-530 kW. Hence, the AC power usage is independent of the required RF output power. To best utilize the available AC power based on the required RF power, an adaptive control methodology is proposed here to change the operation parameters of the klystron, cathode voltage and anode voltage, according to the present RF power. The corresponding operation parameters are applied by the prior tested table which maps the operation parameters with the different saturation RF power. The test results show that the saved energy can be 32% to 11% from 30 mA to 450 mA for both RF plants as comparing to constant operation parameters of 1047 kW AC power.

INTRODUCTION

Since the successful commission of TPS storage ring in 2014 and meet the design specification of beam current up to 520 mA in 2015 [1], the operation of the 3rd generation light source in NSRRC has gradually become mature with the continuous construction of Phase I-II beam lines. Due to the restriction of heat load of in-vacuum undulator [2], the daily operation beam current is set to be 450 mA in 2021 during user beam time. Occasional 500 mA beam current would be applied for some study purpose during machine study period. Besides the high beam loading period, the interval of machine warm up with lower beam current, the decay mode operation of storage ring, or machine maintenance for RF aging of SRF cavity could have lower RF power usage. The RF power requirement for the corresponding beam current is plotted in Fig. 1. For balance power loading, the 2 RF plants shall deliver similar RF power to avoid overloading on one of the RF plants. The maximum RF power requirement of each RF plant is about 230 kW at this stage.

Besides, the construction of 3rd RF system is undergoing between 2019 to 2022 for the more RF power demanding of phase III beam line construction. At the beginning of 3 RF plants in operation, the required RF power would be averaged and each plant would deliver much lower RF power than present status. The lower RF power of 300 kW setting klystron would have lower efficiency. To best utilize the electricity and improve the efficiency of the klystron, the operation parameters of the klystron shall follow the required RF power accordingly. For this purpose, we analyse the operation property of the klystron and propose an adaptive control methodology for changing the operation parameters of the klystron following the required RF power for improving the efficiency of the klystron. Due to practical restriction and operation control limitation, the working parameters for each RF power point is not necessary to be its extremely highest efficiency point. In fact, it is also not possible to have extremely highest efficiency in a dynamic status. However, we still can improve the efficiency of the klystron and save more electricity step by step as we obtain enough experience from practical operation.

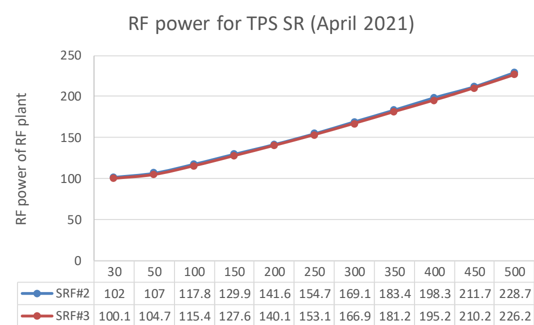

Figure 1: The measured RF power requirement versus of beam current of 2 RF plants for TPS storage ring in April 2021.

METHODOLOGY FOR ELECTRICAL POWER SAVING OF KLYSTRON

For the 300 kW klystron TH2161B from Thales, the factory test report provides 3 sets of operation parameters with optimum DC-to-RF efficiency of more than 50%, 55% and 60% for 150 kW, 200 kW and 300 kW, respectively, as shown in Fig. 2. As the RF output power allocated at about 200-210 kW for SR beam current of 400-450 mA like the curves in Fig. 1, the DC-RF efficiency would be around 40% which is far below the saturation efficiency of 60%.

To improve the efficiency at the required RF power range, a new setting shall be applied as the dot line in Fig. 2. With the new setting, we can roughly improve the efficiency of klystron by about 10% at around 200 kW RF power. To extend the flexibility for various RF power requirement, there shall be more settings for deriving their corresponding optimum efficiency accordingly. In our case, the optimum setting of klystron parameter from RF power from 300 kW to 50 kW in 50 kW steps was found. For the data from factory, the changed setting includes cathode voltage, anode voltage, focus#1 and focus#2 current to obtain optimized DC-RF efficiency. However, it would not be practical to apply 4 variations tuning for efficiency

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improvement. From the operation principle of klystron, the RF output power is mainly determined by the cathode current [3] while the anode voltage determines the cathode current. Besides, the klystron also delivers saturation RF power at constant RF drive power. By the above 2 properties, the maximum available RF power with its corresponding cathode current as shown in Fig. 3.

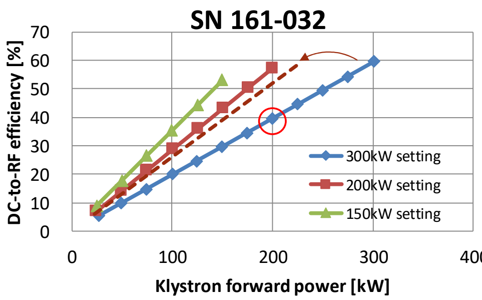

Figure 2: The DC-to-RF conversion efficiency as a function of klystron output power in 3 parameters settings of one klystron.

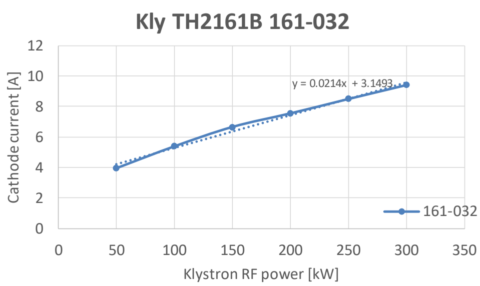

Figure 3: The maximum available RF power versus cathode current.

As there is enough cathode voltage, the cathode current is proportion to anode voltage by the operation principle of klystron [3]. To have enough operation flexibility, two categories of setting for either sweeping or constant cathode voltage are applied for the corresponding maximum RF output power. The focus currents for solenoid are kept as 300 kW setting for its applicability up to maximum power. In this way, an improvement of DC-RF efficiency can be obtained in Fig. 4 at sets of RF power in 50 kW steps.

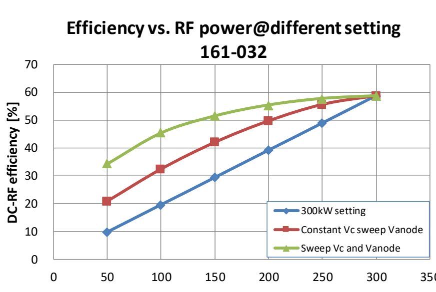

Figure 4: DC-RF efficiency of klystron by three different setting method: 1 sweeping both cathode and anode voltage, 2 sweeping anode voltage only, 3 constant 300 kW setting.

Adjust the Operation Parameters of Klystron by PLC Controller

From Fig. 4, sweeping Vc (cathode voltage) and Vanode can get highest efficiency improvement while the constant Vc with varying Vanode derive the medium efficiency as steady 300 kW setting remains linear efficiency distribution of efficiency versus RF power. For control the operation parameters of the klystron, some preliminary requirement shall be satisfied and developed.

1. External tuning function for cathode and anode voltage: the high voltage power supply shall be able to control its cathode and anode voltage by external analogue voltage source.
2. A controller: The controller shall be able to read the present RF power and output corresponding setting value for cathode and anode voltage by a look up table built inside.

The high voltage power supply, designed and manufactured by Thomson (Now Ampegon, a Swiss company), provide a Siemens PLC controller which can switch cathode/anode voltage control node between internal and external voltage sources. Besides, a small FATEK PLC with analogue I/O extension modules is also developed in NSRRC for reading the present RF power and output high voltage control voltages. A man-machine interface is also developed as shown in Fig. 5.

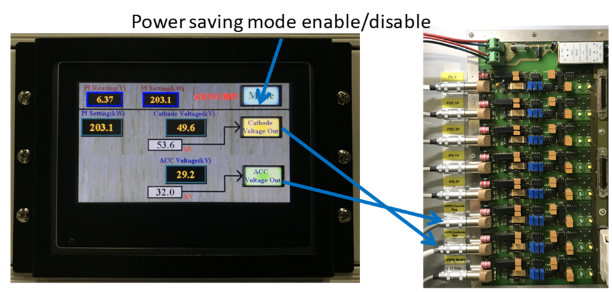

Figure 5: The man-machine interface touch panel can display the read klystron RF forward power and the output analogue signals which control the operation high voltages of klystron.

The PLC controller allow staffs to create loop-up table for mapping the RF power to the sets of cathode and anode voltage. The setting here can determine how the saturation level of the klystron is corresponding to the used operation parameters. There are two sides to trade off. If the saturation power of the used setting is too close to the used RF power, the LLRF control voltage for klystron power would be high and close to its high set point. This way could have higher efficiency but less stable operation ranges. The other side is to give more power to the klystron which could ease the control margin of LLRF but also waste more AC power. A trade-off between efficiency and stable operation margin exists a certain space for people to estimate.

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The Encountered Problem with Storage Ring

Several steps have been applied on the energy saving operation of klystron with storage ring. The steps of their results are list below:

1. One RF plant with power saving control of both cathode and anode voltage: can support storage beam current up to 500 mA without problem. The klystron with power saving feature can save 48% to 12% AC power from 30 mA to 500 mA beam current.
2. Two RF plants with power saving control of both cathode and anode voltage: The test here would cause RF racing problem of both RF plants and let either one of the two RF plants trip due to LLRF overdrive or drive amplifier over drive as shown in Fig. 6. Ideally, the power saving control of both cathode and anode voltage can save most AC energy, however, as there is no klystron phase control loop, the changing of cathode voltage will lead to the change of klystron phase and also the station phase of both RF plants. As station phase changed, the RF power distribution ratio between the two RF plants will also be changed. The co-work of both LLRF phase lock loop and power saving procedure of PLC will result in oscillation like behaviour such that the decreasing of the cathode voltage will lead to higher RF power demanding of that RF plant. As LLRF try to derive more RF power from the klystron which is not able to satisfy that requirement will lead to trip eventually.
3. Two RF plant with power saving control of anode voltage only: To avoid RF power racing problem of step II, the cathode voltage is kept constant and sweeping anode voltage only following the required RF power. This way, the station phases of both RF plants would remain steady and can store up to 500 mA storage beam current without problem.

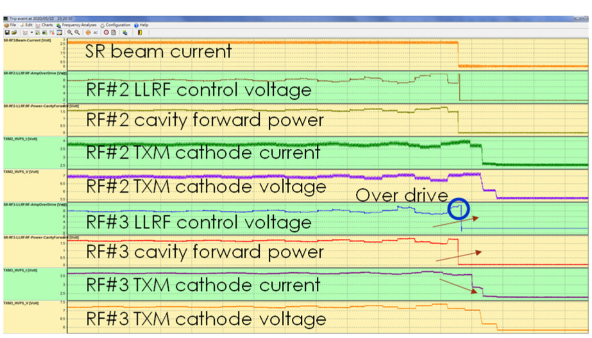
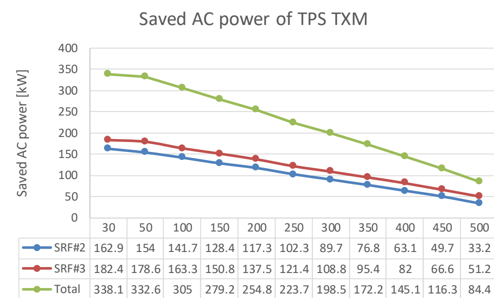


Figure 6: Both RF plants in power saving operation controlling both cathode and anode voltage would cause RF power racing in between and lead to system protection trip.

RESULTS

In step III method, the saved AC power value will depend on how the klystrons are operated close to their saturation point. One concerned point is as the klystron operation near its saturation, the drive voltage of LLRF would become high which could trigger interlock protection easily. To avoid this, the trade-off between power saving and control margin shall be carefully noticed. The saved AC power comparing to original constant 300 kW setting (526 & 521 kW) is shown in Fig. 7. The save AC power percentage is also plotted in Fig. 8. The saved AC power percentage can range from 32% to 11% for the SR beam current of 30 mA to 500 mA at present stage. Further improvement of the power saving effect is possible by pushing the klystron toward its saturation regime and remain enough control margin.



	30	50	100	150	200	250	300	350	400	450	500
SRF#2	162.9	154	141.7	128.4	117.3	102.3	89.7	76.8	63.1	49.7	33.2
SRF#3	182.4	178.6	163.3	150.8	137.5	121.4	108.8	95.4	82	66.6	51.2
Total	338.1	332.6	305	279.2	254.8	223.7	198.5	172.2	145.1	116.3	84.4

Figure 7: The saved AC power of both RF plants as a function of storage ring beam current.

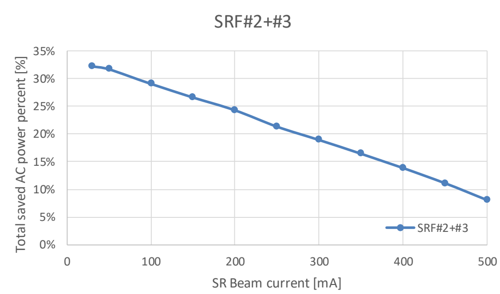


Figure 8: The saved AC power percentage of sum of both RF system as a function of storage beam current.

CONCLUSION

An energy saving operation for storage ring of light source facility is proposed by controlling the operation parameters of klystron close to it saturation point. Several power saving methods are applied for practical storage ring operation up to 500 mA. The power saving method of control both cathode and anode voltage of klystron can only be success on one RF plant. Both RF plants with power saving operation need to keep cathode in constant to avoid station phase change and RF power oscillation between two RF plants like step II method. For step III, the present setting can save up to 338 to 84 kW AC power corresponding to 30 mA to 500 mA beam current for 3 GeV storage in TPS. Further improving the energy saving effect is possible by properly controlling the klystron phase and LLRF controller.

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