Adaptive control of klystron operation parameters for energy saving at storage ring of TPS

Session: MC07, THXC -- Thursday Oral Parallel C, 05/27/2021 1100 – 1200, Oral Session C
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IPAC2021
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Introduction

- Two RF plants with 500 MHz 300 kW transmitter, LLRF, RF feed lines and a superconducting module are working in storage ring (SR) of Taiwan Photon Source (TPS).
- The beam energy is 3GeV with maximum beam current of 500 mA.
- The required RF power for each RF plant is about 226-228 kW in April 2021 for total 17 beam lines with 450mA beam current in daily routine operation.
- A third RF plant is being installed from 2019-2022 to support more IDs after phase III beamline construction.

![RF power for TPS SR (April 2021)](image)
Motivation

- The fixed operation parameters of klystron has lower DC-RF efficiency as RF output is not closing its saturation
  - Such condition is not energy efficient
- To afford maximum beam current of TPS SR, the setting of klystron is for maximum RF power (300kW) of each RF plant
- However, SR do not always run at its maximum beam current, the RF power of each plant is about 227kW for 450mA beam current in 2021
- Besides, a third RF plant is going to join the SR operation for more IDs after 2022
- Beam power requirement will be shared by three RF plants and each RF plant will deliver less RF power in the beginning (before completing all phase III BLs)
- Try to make klystron to be more efficient in such situation
Motivation

- Upon specification, the factory test data of Thales klystron TH2161B give 3 sets of operation parameters for 150kW, 200kW and 300kW saturation power.
- Assume the required RF power is 200kW for 400mA beam current, the 200kW setting of klystron is not enough and 300kW setting would have lower efficiency (40%) at this point.
- If we can move the saturation power from 300kW toward 200kW, the klystron can have higher efficiency than 40%.
- Higher efficiency means less energy consumption and save electricity.

![Klystron in TPS](image_url)

![DC-to-RF efficiency](image_url)
Operation principle of klystron

- Here, the detail theory of single beam klystron won’t be discussed
- Just observe the drive RF power and its saturation power at different setting
- Obviously, the klystron will reach its saturation output RF power at nearly identical drive RF power
- We can find more saturation RF power values with different settings by fixing drive RF power (dot curves)
Various setting for various saturation RF power of klystrons

- According to above assumption, we can find much more higher efficiency settings in 50kW steps in two category
  - Constant cathode voltage but sweeping anode voltage
  - Sweeping cathode and anode voltages
- We can find the anode voltage (= cathode current) determines the maximum saturation RF power
- But varying cathode voltage can have higher DC-RF efficiency

![Graph 1: Voltage vs. RF power@different setting](image1)

![Graph 2: Efficiency vs. RF power@different setting](image2)
Adjust the operation parameters of klystron by PLC controller

- The high voltage power supply designed by Ampegon (Swiss company) can adjust its cathode/anode by external tuning voltage.
- A PLC controller is developed for tracking the present RF power and change the setting of cathode/anode voltage of high voltage power supply accordingly.
- The setting value is obtained from the test curve of the klystron without changing focus (solenoidal) current.

Power saving mode enable/disable
Encountered problems

- The saturation of LLRF
  - LLRF will saturate as the klystron is closing its saturation RF power
  - At such condition, LLRF cannot control the klystron power anymore and easily trip as it touches its high set point
- The RF station phase will change as cathode voltage is tuning
  - Obviously, the electron speed (energy) of klystron is determined by the cathode voltage and the RF output power phase will also vary with the cathode voltage
  - As klystron phase is changing, cavity phase lock loop of LLRF will start to change its phase shifter and also change the station phase of each RF plant
  - The RF power balance among two sets of RF plant will start to change
  - The PLC will also start to track the changing RF power and adjust its setting for klystron
  - However, the reaction speed of PLC is far slower than LLRF
  - An oscillation like condition will happen
RF power oscillation between 2 sets RF plant

- At sweeping cathode and anode voltage power saving setting, one of the two RF systems will trip finally as drive power reaches its high set point
RF power oscillation between 2 sets RF plant

- At sweeping cathode and anode voltage power saving setting, one of the two RF systems will trip finally as drive power reaches its high set point.
How to avoid control problems?

- The setting of klystron shall not just at its saturation power
  - Give more DC power to klystron (lower efficiency) and left control margin to LLRF
- Avoid sweeping cathode voltage
  - Keep cathode voltage at constant: no change station phase
  - Save less power but stable operation

### Voltage vs. RF power@different setting

- Constant cathode voltage
- Varying anode voltage
The power saving effect

- Saved AC power: compared to original constant setting
  SRF#2: 526.4 kW AC power
  SRF#3: 521.4 kW AC power

- The horizontal scale is SR beam current
  - As beam current is lower, the energy saving effect will be higher
  - The energy saving effectiveness is obvious for lower RF power requirement of each TXM

![Graph of Saved AC power of TPS TXM](image1)

![Graph of Total saved AC power percent %](image2)
Power saving results of practical operation with SR beam current

- As turning on energy saving module:
  - The AC power consumption is lower and will change with the variation of SR beam current
- For 450mA SR beam current (daily operation value in 2021)
  - SRF#2: 533kW → 482kW, ΔP=51kW
  - SRF#3: 526kW → 461kW, ΔP=65kW
- Total: 116kW (11.4% power saving)

Before turn on energy saving  After turn on energy saving

| SRF#2 TXM AC power | SRF#3 TXM AC power | SRF#2 TXM AC energy | SRF#3 TXM AC energy | TPS SR Beam current |
Power saving effect statistic

- The power saving effect will be determined by the beam current distribution among machine operation shifts.
- A statistic of beam current usage is listed below,
  - So far, the maximum saved energy is around **86000 kWh** in a routine user beam time per month.

<table>
<thead>
<tr>
<th>Item</th>
<th>Duration (hr)</th>
<th>Percent [%]</th>
<th>Saved AC power [kW]</th>
<th>Saved AC energy /month [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPL aging</td>
<td>4</td>
<td>0.56</td>
<td>250 kW</td>
<td>1000 kWh</td>
</tr>
<tr>
<td>Low beam (30mA) current machine study</td>
<td>24</td>
<td>3.37</td>
<td>338 kW</td>
<td>8112 kWh</td>
</tr>
<tr>
<td>High beam (500mA) current machine study</td>
<td>72hr (3days)</td>
<td>10.11</td>
<td>84 kW</td>
<td>6048 kWh</td>
</tr>
<tr>
<td>User beam time (450mA)</td>
<td>612hr (25days+3shifts)</td>
<td>85.96</td>
<td>116 kW</td>
<td>70992 kWh</td>
</tr>
<tr>
<td>Total</td>
<td>29day+16hr (8hr OFF)</td>
<td>100</td>
<td></td>
<td>86152 kWh (11.4% power saving)</td>
</tr>
</tbody>
</table>
Conclusion & discussion

- An adaptive control of operation parameters of klystron by PLC can have higher DC-RF efficiency and save energy.
- Tuning the cathode and anode voltage both can save much more energy but will change RF plant station phase significantly and cause system trip eventually due to RF power racing between two RF plants.
- Add klystron phase lock loop may fix the station phase of RF plant as cathode voltage is tuning → save more energy.
- Tune anode voltage only according to the required RF power will save less AC power but have constant station phase.
- The principle of energy saving operation:
  - Maintain proper control margin: LLRF cannot work too close to its saturation point → loose the setting and spend more energy.
  - The setting of lower RF power can save more energy.
- Besides energy saving, the stability of system still remains the major concern.
Thanks for your attention