ISIS INJECTOR 2 MW PULSED RF SYSTEM POWER SUPPLY UPGRADE

R J Anderson, M Keelan, STFC, Rutherford Appleton Laboratory, Harwell Oxford, Didcot, OX11 0QX, United Kingdom

Abstract

The ISIS pulsed neutron and muon source [1] uses a 4-stage 70 MeV linear accelerator powered by TH116 triode valves [2]. The TH116 anode supply capacitor banks have until recently been supplied by conventional 6-pulse silicon controlled rectifier (SCR) bridges delivering up to 40 kV at 5 A direct current. This dated system has become increasingly difficult to maintain.

Early trials of an upgraded system using modern, compact, capacitor charging, switch mode supplies (SMPSs) resulted in severe supply power quality issues due to the way the SMPSs responded to the pulsed nature of the current demanded from the capacitor banks. Measurements and Spice simulations of the old and replacement supplies allowed the power quality issues to be investigated and an additional external-to-the-SMPS regulator control loop to be developed. The new SMPSs operating with the additional control loop have been tested successfully on several of the linear accelerator stages and are now in continuous operational use. The process of replacing all the original SCR 6-pulse bridges is now well advanced and the operational benefits for ISIS are becoming evident.

ORIGINAL SYSTEM DESCRIPTION

The TH116 triodes are currently operated with cathode modulation [3] to prevent spurious oscillation between beam pulses and limit anode dissipation while the anode voltage is permanently applied. The RF drive to the triodes is pulsed with a pulse length of 300-400 μs and with a repetition rate of 50 Hz. Four 40kV supplies are used on the ISIS injector, one for each of the 202.5 MHz linac tanks.

The original anode power supplies used SCRs to control the 50Hz 3-phase primary side of a 415 V to 34 kV step up transformer with a conventional 6-pulse bridge rectifier fed by the high voltage secondary. Each power supply was designed to continuously recharge a bank of capacitors to voltages of up to 40kV; creating a 50 μF reservoir for each TH116 triode amplifier end stage. The SCR firing angle and thus capacitor bank charging rate was controlled by a machine code program running on a now obsolete RCA1802 microprocessor. The SCR firing angles were controlled by an 8-bit counter and its value was cyclically incremented and decremented by the microprocessor according to the deviation of the capacitor bank voltage from the desired set point.

SWITCH MODE UPGRADE

After over 20 years of service the original system was beginning to fail due to general wear and tear, particularly on the circuit board to backplane connectors for the control system. Depletion of the stock of available spare parts made replacement a priority. In addition the use of SMPSs promised gains through operational reliability, ease of maintenance, mean time to repair and space saving.

The Lambda 303 SMPS [4] was selected as a replacement for the original systems. The 303 series is primarily intended for capacitor charging applications, providing a fast constant current charge to the capacitors and then switching to voltage regulation mode once the programmed voltage is reached. Between 3 and 5 modules each delivering up to 1.125 A at up to 40 kV were assembled into a single 19 inch rack and connected to supply each TH116 end stage.

POWER QUALITY ISSUES

First trials with the new power supplies were very promising however as more of the linac tanks were switched over to the new supplies several problems appeared that were subsequently traced to power quality issues. The RF system driver and end stage valve filaments use zero crossing detection based SCR control and these systems started to blow fuses. The entire injector is fed from an 11 kV substation via a pair of 11 kV to 415 V three phase transformers and these transformers started to produce excessive levels of noise and vibration. Plans to transfer all the tanks to the new supplies had to be put on hold while the power quality issues were fully understood

Although the supply voltage waveforms didn't appear excessively distorted, monitoring of the currents drawn from the substation transformers by the new supplies quickly revealed the source of the problems. The new SMPSs were initially drawing the highest current they could to recover the capacitor bank voltage after each RF pulse and then drawing almost nothing for the rest of the inter-pulse period. The ISIS pulse repetition rate is close to the mains supply frequency and the currents drawn from the supply transformer by the SMPS tended to be drawn from just one half cycle of the supply waveform. As a result the SMPSs were drawing supply currents with a high average DC value. The DC current component appeared to be driving the supply transformer magnetic circuit into saturation and also appeared to be causing the problems with the filament controller zero crossing detectors. Further tests showed that it was possible to limit the rate at which the new SMPSs draw current from the substation transformers. The charging rate of the capacitor bank could be controlled using a 500 Hz square wave of varying mark to space ratio to modulate the SMPS inhibit input. Selecting the correct mark to space ratio allowed the positive and negative going currents drawn from each supply phase to be equalised eliminating the power quality related symptoms suffered previously.

ISBN 978-3-95450-115-1

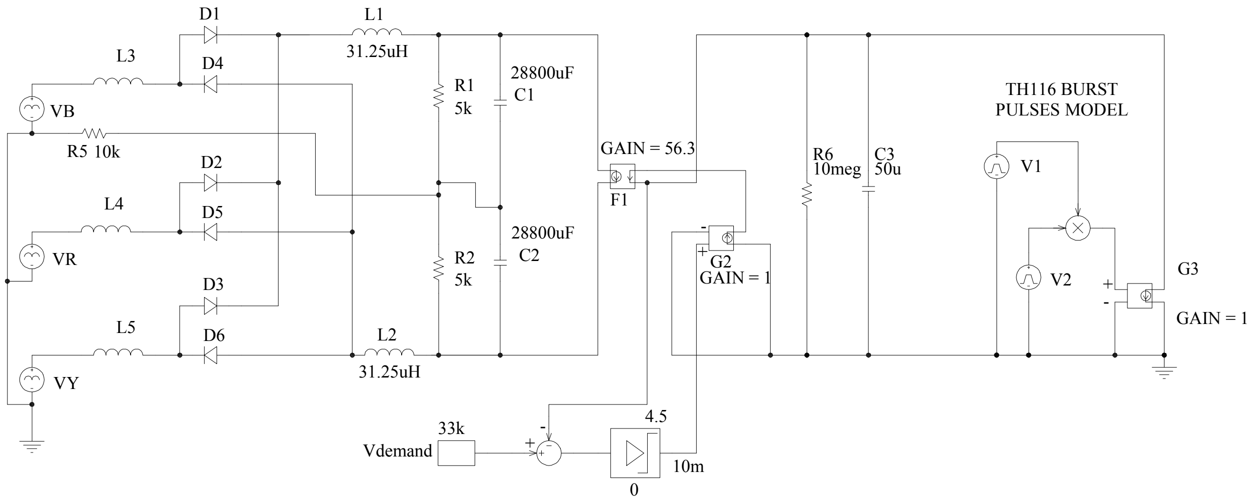

Figure 1: Simplified SPICE model of 4 switch mode power supplies parallel connected.

Note that the ISIS substation transformers still typically deliver 415V or more even though the nominal UK supply voltage was reduced in the 1990s to 400V to harmonise with the rest of the European Union [5]. The same is true of the as-measured supply voltages in the majority of the UK, harmonisation was little more than a formal change in voltage tolerances.

SYSTEM SIMULATION

Spice simulations of the SMPS were used to develop a pulse width modulation circuit to dynamically adjust the duty cycle of an inhibit pulse. Simulations were first performed to replicate the asymmetries seen on the AC supply currents with the SMPS. The model used for this is illustrated in Fig. 1.

The substation transformer is modelled in the left hand part of Fig. 1. as three 50Hz 240V RMS voltage sources with a fixed 120 degree phase shift between each source. The supply inductance of the substation transformer is modelled by the three 150uH inductors L3, L4 and L5. Four SMPSs operating in parallel are represented by the 6-pulse diode bridge D1 to D6, the post rectification inductors L1 and L2 and the capacitor bank C1 and C2 with divider resistors R1 and R2. The remaining parts of the SMPSs are modelled with Spice "Analogue Behavioural Models" (ABMs) to represent the overall behaviour of the SMPS control circuit without the need to model every component this contains.

The current controlled current source ABM F1 draws current from the SMPS internal ±293V pass banks in proportion to the current delivered to the 40kV reservoir by the voltage controlled current source ABM G2. G2 is controlled by a limiting amplifier. The limiting amplifier is in turn driven by the error signal derived from the difference between the 33kV set-point and the instantaneous voltage on the 40kV reservoir. The 40kV reservoir is represented by R6 and C3. The current drawn by the TH116 end stage is modelled by the controlled current source G3. For the simulation shown here G3 is controlled to draw a steady current but it can also draw current in repetitive bursts with a pause between each burst to investigate transient ISIS beam loading effects.

Fig. 2 shows the three simulated phase currents drawn from the AC supply with a steady current drawn by the TH116. Over the time frame of 300 ms displayed the red phase current (black line) can be seen drifting through a negative peak value while the blue phase (grey dots) rises to a positive peak value. The yellow phase (grey line) drifts from a positive to a negative peak. Most notably while near the peak values there is also a strong DC component to each phase current.

The ISIS pulse repetition rate is not locked to the AC power supply frequency; hence when monitored on an oscilloscope the current waveforms appear to gradually drift through the three phases of the AC supply; typically over a period of several tens of seconds. The RF pulse rate in this simulation has been deliberately reduced by 1 ms to speed up this effect in order to show a range of wave shapes in a shorter time scale than would be seen on ISIS. In reality one phase of the supply transformer will generally experience the same DC component for many tens of seconds before the DC current component drifts on to the next supply phase.

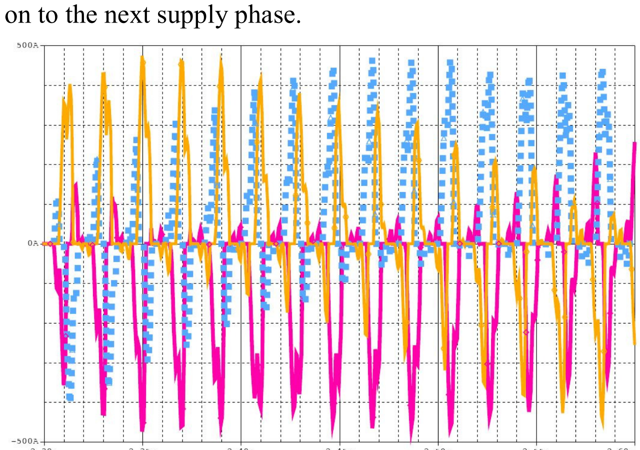

Figure 2: Spice simulation of the basic SMPS showing currents drawn from each phase of the AC supply.

NEW CONTROL LOOP

Having verified the validity of the basic SMPS Spice model, a new control loop acting dynamically on the SPMS inhibit inputs could now be developed. The inhibit pulse duty cycle had to rapidly adapt to changes in current drain from the capacitor bank while ensuring both a minimal bank voltage variation and a steady supply transformer current demand.

The spice model of the chosen scheme is illustrated in Fig. 3. In the revised model the set point that directly controlled the SMPS output in Fig. 3 now drives a new control loop and a small offset is added to the set point to drive the SMPSs indirectly (in the simulations, offsets of not less than 1kV were found to be necessary for this control scheme to operate as intended). The SMPS control loop is the same limiting amplifier as shown in Fig. 3. but an additional multiplier has been added between the output of the limiter amplifier and the voltage controlled current source G2 to approximate the time averaged effect of a pulse width modulated inhibit signal.

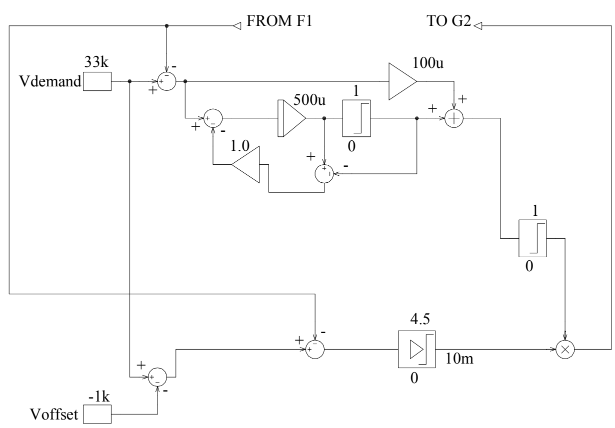

Figure 3: Spice model of the new inhibit control loop.

The new control loop consists of a proportional gain amplifier and an integrator. Additional components have been added round the integrator to prevent integrator wind-up.

Simulations were tried with various values of proportional and integral gain applied to the inhibit control loop to find the optimum settings. If the gains are set too high then the multiplier driving G2 is driven on aggressively for part of the inter-pulse period and then almost off until the next pulse. Optimum gain values where found that resulted in a steadier drive signal to the multiplier without compromising too far on the control loop's ability to cope with rapid changes in voltage on the 40kV reservoir such as may occur during the conditioning of a new TH116.

Following Spice simulation using the ABMs, the control loop design was then converted to a circuit with operational amplifiers driving a UC3525 Pulse Width Modulator (PWM) integrated circuit (IC). The entire analog circuit was also modelled in Spice before being built and successfully tested on one linac section.

OPERATIONAL EXPERIENCE

After conversion to a printed circuit layout, the control loop was installed on each of the first two linac sections and these have now been operated continuously with the SMPSs since April 2010. Over the following year problems were encountered due to occasional failure of the PWM IC. These failures were generally associated with breakdowns or water interlocks in the rest of the RF drive chain. Additional surge suppression was subsequently added between the PWM IC output and the SMPS inhibit input and during the following year no further control loop failures occurred.

In October 2011 a new TH116 had to be installed and conditioned on the 4^{th} linac section. The original SCR controlled 40 kV supply had become so unstable that it was impossible to condition the new TH116 in circuit and the decision was then made to transfer this linac section to run on the SMPS's too, leaving only one linac section (for the 3^{rd} linac tank) still operating with the original SCR controlled supply.

Very occasionally one of the SMPS units has developed a fault. Whereas in the original SCR controlled supply a fault would have caused ISIS down time during repair, with several SMPSs operating in parallel it has always been possible to operate the affected linac section from the remaining good units without interruption to ISIS operations and to schedule fitting a replacement during an ISIS off period.

The "modulator pens" feeding RF power to both the 1^{st} and 2^{nd} linac sections have now been re-organised to make use of the space released by removing both the older 40kV and 20kV SCR controlled transformer rectifier components. The older 20kV supplies used to feed the RCA 4616 driver stages but these had previously been replaced with SMPS alternatives. This physical reorganisation has also improved accessibility and ease of maintenance for the entire RF drive chain. The final linac section was recently transferred over to the new supplies allowing reorganisation of the final two modulator pens to start at the next suitable ISIS shutdown.

REFERENCES

[1] http://www.isis.stfc.ac.uk/
[2] D.J.S. Findlay, "ISIS – Pulsed Neutron and Muon Source", PAC'07, p. 695 (2007); [6]
[3] B. Brady, C.W. Planner, A.F. Stevens, "Cathode Modulation of High Power RF Output Triodes of the ISIS Linac", EPAC'98, p. 1909 (1998); [6]
[4] http://www.us.tdk-lambda.com
[5] BS7697:1993, The British Standards Institution
[6] http://www.JACoW.org

ISBN 978-3-95450-115-1