

A Factory Prototype of High Voltage Power Supply Module Incorporating Piezoceramic Transformer

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Abstract

The article describes a factory prototype of the high voltage power supply module incorporating a piezoelectric ceramic transformer. A Japanese company has developed a factory prototype of the module to verify performance, intending to manufacture commercial products for industrial use. The module is tested from the viewpoint of availability in LHC experiments. The module is capable of supplying stabilized high voltage from 2500 V to 4000 V to a load of more than 25 M Ω at efficiency of better than 50 percent from a supply voltage of 3 V under a magnetic field of 1.5 tesla. Ripples on the high voltage are a few tens of millivolts in peak-to-peak amplitude. The module is protected against short-circuiting. The module was irradiated by Co-60 source up to 2 krad without degradation in performance. The module is 110 mm in length, 100 mm in width and 15 mm in thickness. The module is provided with interface so that the module can be kept under external control. The modules are installed in a crate with a crate controller of network capability. The crates are networked and the modules in the crates are controlled through the network.

I. HIGH VOLTAGE POWER SUPPLY MODULE

The high voltage power supply module incorporates a ceramic transformer [1, 2, 3]. The ceramic transformer takes the place of the conventional magnetic transformer. The ceramic transformer utilizes piezoelectric effect to generate high voltage. The ceramic transformer generates high voltage efficiently. The ceramic transformer is constructed from a ceramic bar and does not include any magnetic material. So the transformer is free of leakage of magnetic flux and can be operated efficiently under a magnetic field. The ceramic transformer can be operated under such strong magnetic field as 1.5 tesla [3]. An inductance element is required to obtain efficient high voltage generation, being implemented by an air-core coil. The transformer is shaped symmetrically in the lengthwise direction and operated in the longitudinal vibration mode.

The power supply module is composed of divider resistors, an error amplifier, a voltage controlled oscillator (VCO), a driver circuit, the ceramic transformer and a Cockcroft-Walton (CW) circuit. The VCO generates a driving frequency of a sinusoidal voltage wave, which drives the ceramic transformer. The VCO supplies the driving frequency to the driver circuit where the sinusoidal voltage wave is generated synchronized

with the driving frequency. The sinusoidal voltage wave is amplified in voltage by the transformer and then supplied to a Cockcroft-Walton (CW) circuit where the sinusoidal wave is amplified further in voltage and rectified. An output high voltage is produced at the output of the CW circuit.

A. Feedback

The high voltage is stabilized by feedback. The output voltage is divided by the divider resistors and fed to the error amplifier to be compared with a reference voltage. The output of the error amplifier is supplied to the VCO which generates the driving frequency of the sinusoidal voltage wave. The sinusoidal voltage wave drives the transformer through the driver circuit. Voltage amplification of the transformer depends on the driving frequency. The dependence is utilized for stabilization. The driving frequency generated by the VCO is controlled by the output of the error amplifier. So magnitude of the amplification is adjusted by controlling the driving frequency, which stabilizes the output high voltage.

The ceramic transformer includes an internal resonance circuit. The transformer input voltage is amplified at the output, with the input to output voltage ratio being an amplitude ratio that shows a resonance as a function of the driving frequency. The resonances obtained by the measurements are shown in Fig. 1 for various values of load. The output voltage of the transformer was measured by a probe, whose input impedance is 1 M Ω paralleled with capacitance of about 15 pF.

The range of the driving frequency is designed to be higher than a resonance frequency of the ceramic transformer as shown in Fig. 2. So the feedback increases the driving frequency when the output voltage is higher than the reference voltage at the input of the error amplifier. Similarly, the driving frequency decreases when output voltage is lower than the voltage specified by the reference voltage.

B. Breakdown of Feedback

If the load of the module falls within an allowable range, the driving frequency is maintained higher than the resonance frequency such that the feedback is negative as designed. The allowable range of load is sufficient in most cases, but it cannot cover, for example, short-circuiting the output voltage to ground. When the load deviates beyond the allowable range, the driving frequency may decrease below the resonance frequency; a condition that will not provide the required

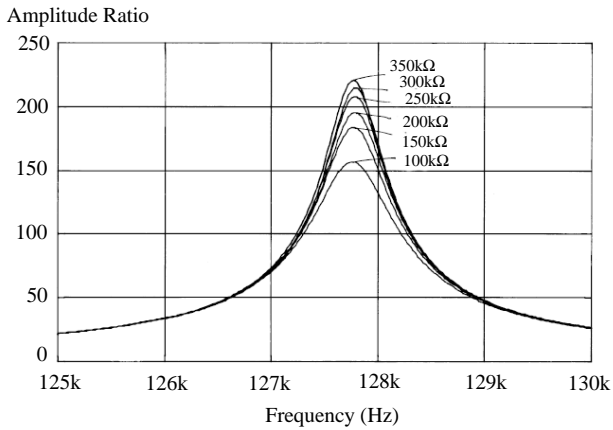


Figure 1: Resonances shown by piezoceramic transformer for various values of load

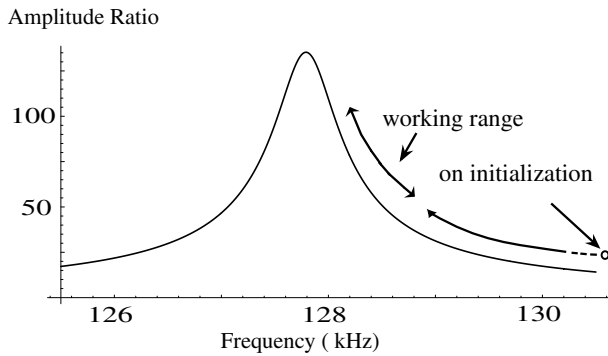


Figure 2: Range of driving frequency for feedback

negative feedback, i.e., positive feedback locks the circuit such that it is independent of load. In order to recover the negative feedback, the driving frequency must be reset externally in addition to removing the load.

II. A PRODUCTION PROTOTYPE OF HIGH VOLTAGE POWER SUPPLY MODULE

A Japanese company¹ developed a factory prototype of the power supply module to verify performance, intending to manufacture commercial products for industrial use. The prototype accepts various ceramic transformers. So the prototype can be tailored to such modules that comply with diverse requirements.

The company has developed a production prototype of such a high voltage power supply module that satisfies specifications required by LHC experiments. We have tested the module from the viewpoint of availability in LHC experiments, where the module is capable of supplying stabilized high voltage from 2500 V to 4000 V to a load of more than 25 M Ω at efficiency better than 50 percent from a supply voltage of 3 V under a

magnetic field of 1.5 tesla. The module is 110 mm in length, 100 mm in width and 15 mm in thickness.

The transformer employed in the module is a small, low-profile, highly efficient transformer. The transformer amplifies voltage by more than 150 times with a load of 150 k Ω (Fig. 1). The maximum power rating of the ceramic transformer is about 4 W. Fig. 3 shows the circuitry in the high voltage power supply module before resin treatment. High voltage circuits are coated with silicon so as to improve isolation in voltage.

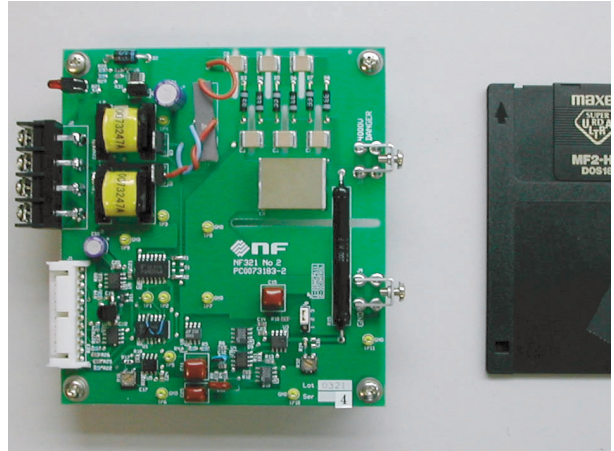


Figure 3: Circuitry in high voltage power supply module and a floppy disk

A block diagram of the module is shown in Fig 4. The module is installed in a crate, which powers the modules. The crate supplies direct-current voltages for the driver circuit and for the circuitry in the module. The module is provided with interface so that the module can be kept under external control.

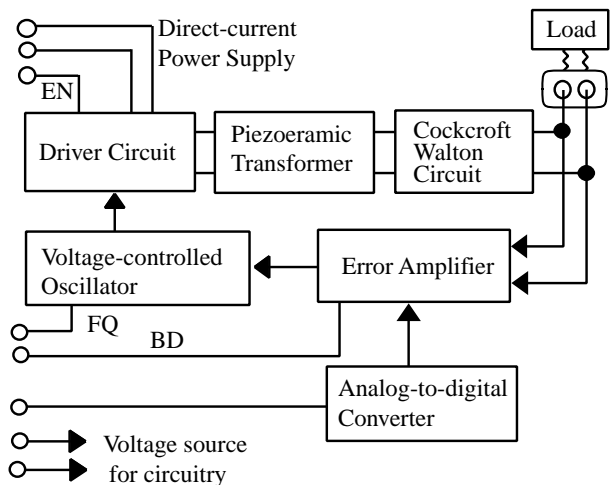


Figure 4: Block diagram of high voltage power supply module

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A. Protection

The load deviated beyond the allowable range causes the breakdown of feedback decreasing the driving frequency beyond the resonance frequency. Such decrease of the driving frequency, accompanied with the breakdown of the feedback, lowers the output voltage. Thus the breakdown of feedback works as protection against, for example, the short circuit of the output high voltage.

B. Interface to External Control

The module is provided with interface terminals so that module can be controlled externally. Most functions of the module are brought under the external control through the terminals. The module is switched on and off externally by an enable (EN) terminal.

C. Output Voltage

The reference voltage, supplied to the error amplifier, is generated by a digital-to-analog converter under the external control. The reference voltage defines the high voltage at the output. So the high voltage is assigned externally through the control of the converter.

D. Detection of Feedback Breakdown

A VCO voltage, which is the output of the error amplifier, controls the driving frequency. The feedback breakdown is caused by deviation of the VCO voltage from its normal range. The deviation is detected by a voltage comparator, the output of which is supplied to a breakdown (BD) terminal. The assertion of the BD terminal makes the feedback breakdown to be recognized. Once the breakdown is acknowledged, procedure for recovery from the breakdown is managed externally.

E. Recovery from Feedback Breakdown

Following external control, the module is managed so as to be recovered from the feedback breakdown, where firstly the reference voltage is reset, which initializes the driving frequency, and secondly the reference voltage is increased to a prescribed value so as to restore the high voltage. The recovery is attained through the control of the analog-to-digital converter.

F. Current Monitor by Driving Frequency

If both the output voltage and the supply voltage are known beforehand, the driving frequency at which the transformer is driven depends on the magnitude of the load. So the output current can be estimated from the driving frequency.

The output of the VCO is supplied to a frequency (FQ) terminal. The VCO outputs the driving frequency on a square wave, which enables a simple logic circuit to count pulses. The driving frequency, obtained by counting pulses over a fixed time interval, allows calculating the magnitude of the load based on the shift of the driving frequency. The driving frequency from the FQ terminal allows coarse estimation of the output current.

III. PERFORMANCE

Performance was measured for six modules; one module of the original prototype and five modules of the production prototype. The output of the module was loaded with 25 M Ω . The voltage fed to the circuitry in the module is 7 V, and the voltage supplied to the driver circuit is 3 V.

The high voltage at the output of the module is defined by the reference voltage. The voltage at the output was measured against the reference voltage. In Fig. 5, the voltage at the output is plotted against the reference voltage. The plot shows good correspondence.

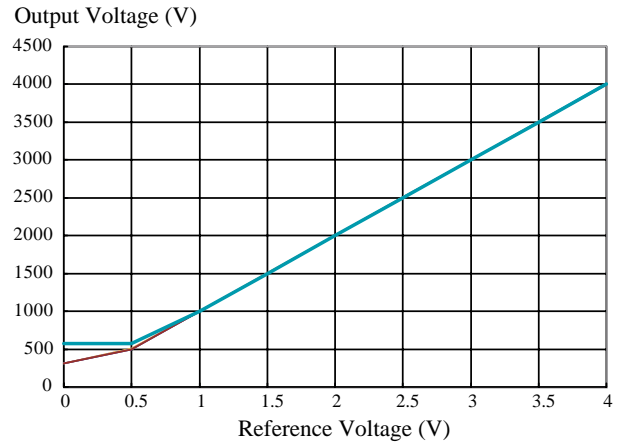


Figure 5: High voltage versus reference voltage

The high voltage at the output is not strictly equal to the high voltage defined by the reference voltage. The voltage at the output may deviates from the high voltage. The deviation was measured against the reference voltage. In Fig. 6, the deviation is plotted in percentage terms against the reference voltage.

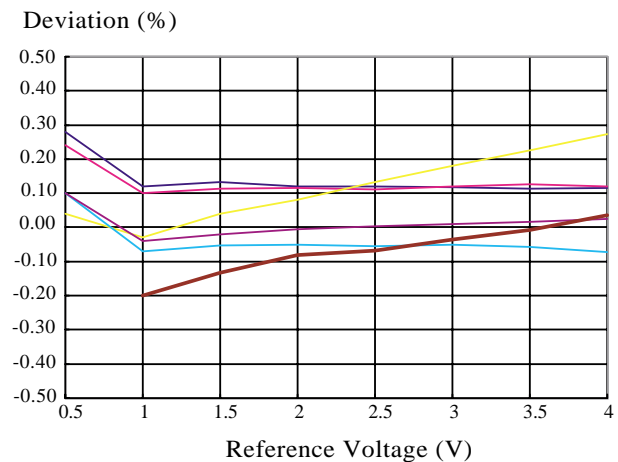


Figure 6: Deviation of output voltage in percentage terms from high voltage specified by reference voltage

The current consumed by the circuitry in the module was measured. Fig. 7 shows the current supplied in terms of milliampere, where the supplied voltage is 7 V. The current is

kept almost constant with respect to the reference voltage.

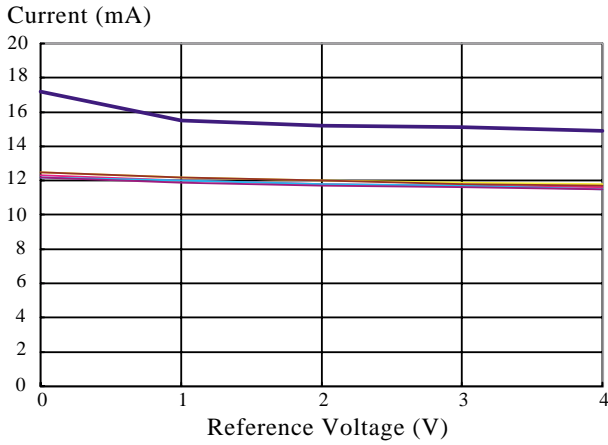


Figure 7: Current consumed by circuitry in module

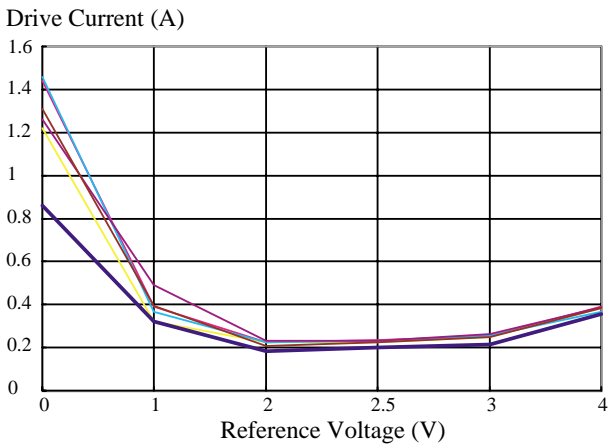


Figure 8: Current supplied to driver circuit

The current supplied to the driver circuit was measured. Fig. 8 shows the current in terms of ampere against the reference voltage, where the supplied voltage is 3 V. The current varies with the reference voltage, which shows the dependence of the current on the driving frequency. The current is converted to high voltage efficiently with such the driving frequency that realizes zero-voltage switching. The efficiency degrades with the driving frequency that is too high for the zero-voltage switching. Inefficiency is caused for the range of the reference voltage below 2 V.

The module generates the high voltage from the power supplied to the driver circuit. The power of the high voltage delivered to load is computed from the output voltage and the current. Efficiency is the ratio of the supplied power to the delivered power. In Fig. 8, the efficiency is plotted against the reference voltage in percentage terms. From Figures 8 and 9, discrepancy in efficiency was found between the original prototype and the production prototype. The efficiency is improved by the next version of the production prototype.

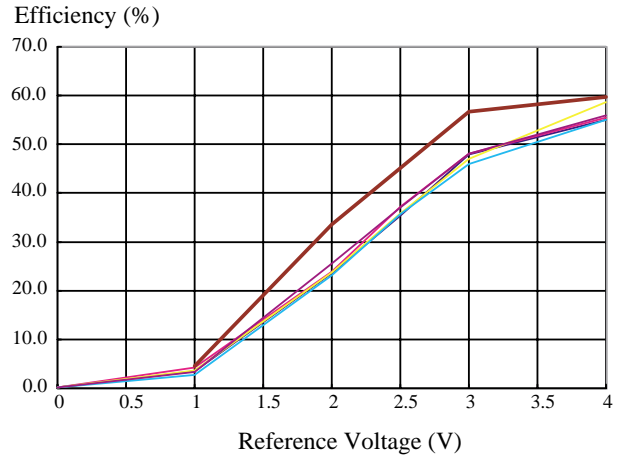


Figure 9: Ratio of power supplied to the driver circuit to power delivered to load

IV. RIPPLES ON HIGH VOLTAGE

Amplitude of ripples on the high voltage was measured against the reference voltage. In Fig. 10, the peak-to-peak amplitude of the ripples is plotted in terms of millivolt. The high voltage from the module, being loaded with 25 M Ω , is supplied to an amplifier by AC coupling. The coupling capacitor is 100 nF. The input impedance of the amplifier is 124 M Ω . The output of the amplifier is monitored by an oscilloscope. The trace is shown in Figure 11, where the vertical and the horizontal divisions are 10 mV and 2 μ sec respectively. From Figures 10 and 11, it can be seen that the ripples on high voltage are less than 50 mV in peak-to-peak amplitude.

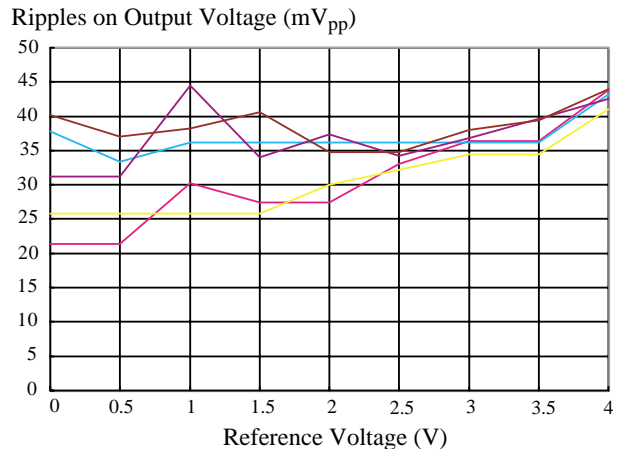


Figure 10: Peak-to-peak amplitude of ripples on the high voltage

V. RADIATION TEST

Firstly the module was irradiated by Co-60 source up to 2 krad without degradation in performance. The module being scrutinized, no shift in characteristics was found. Extensive test is planned. Radiation test by a neutron beam is now scheduled.

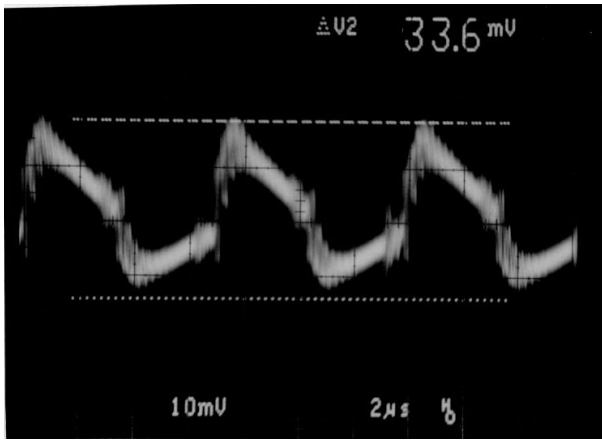


Figure 11: Trace of ripples on high voltage

The test at the level of components will begin soon.

VI. CRATE AND CRATE CONTROLLER IN NETWORK

The high voltage power supply modules are installed in the crates with network capability. A crate controller resides in each crate. The crate controller can control the module. The controller is enabled to switch on and off the module and set the output voltage. The controller can detect the short circuit of the high voltage and control its recovery. The controller can also monitor the output current. Most functions of the module are brought under the controller.

The crate controller, capable of communicating with other crate controllers over twisted-pair cables, networks a number of the crates. So function of the module kept under the control of the crate controller is managed through the network. Most functions of the module are under the control of the crate controller. The module is turned on and off through the network. The output high voltage is set through the network. The output current is also monitored through the network. The crate controller detects the breakdown of the feedback and reports the detection through the network, which helps to fix the cause of the breakdown. The crate controller, following instructions received from the network, manages recovery from the breakdown.

The crate controller enables crates to network intelligently. The crate controller has all the built-in communications and control functions to implement. These crates may be easily integrated into distributed intelligent control networks.

VII. CONCLUDING REMARKS

The crate and the crate controller are under development. The power supply module will be further improved before commercial production. The module is reduced further in size. The performance of the module is scrutinized. Its characteristics are analyzed in details.

VIII. REFERENCES

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