A New Energy Recovering DeQing for Line-Type Pulse Modulators

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Abstract

In a typical line-type modulator the amplitude of the pulse forming network (PFN) voltage is controlled by a deQing circuit (resistor or resistor and capacitor in parallel, and SCR), connected to the secondary of the charging choke. The energy stored in the charging choke at the moment of deQing is usually dissipated in the deQing resistor. For the SLAC modulator, for instance, the typical value of average power dissipated in this resistor is 5-10 kW. At the moment there is only the SLAC energy recovering deQing system, which is based on accumulation of the deQing energy into a capacitor bank, from where it is then transferred by inverter to the main ac line.

This paper describes a new simple energy recovering deQing system. Other than the SLAC deQing system, the energy accumulated in the storage capacitor bank during a current PFN charging cycle is being transferred directly into the PFN capacitors, before the following charging cycle is started. The preliminary low-voltage model investigation shows that this scheme, besides reduction of the power consumption and elimination of the powerful deQing resistor along with it's cooling system, allows to increase the level of deQing and insures a stable modulator output voltage over a wide range of the main ac voltage.

Introduction

A typical line-type pulse modulator consists of a pulse forming network (PFN), which is resonantly charged from a dc power supply through a charging choke, and discharging into a load using a thyratron or SCR as a switching element. The amplitude of the PFN voltage is controlled by a deQing circuit (resistor or resistor and capacitor in parallel, and SCR), connected to the secondary of the chargihg choke [1, 2]. The energy stored in the charging choke at the moment of deQing is usually dissipated in the deQing resistor. For the SLAC modulators [3] the typical value of average power dissipated in this resistor is 5-10 kW, for level of deQing 5-10 %, correspondingly. At the moment there is only the SLAC energy recovering deQing system, which is based on accumulation of the deQing energy into a capacitor bank, from where it is then transferred by inverter to the main ac line [3].

A new simple energy recovering deQing scheme has been proposed during the design of a line-type pulse modulator for the S-Band Test Facility at DESY [4]. Other than the SLAC energy recovery deQing system, the energy accumulated in the storage capacitor bank during a current PFN charging cycle is being transferred directly into the PFN capacitors, before the following charging cycle is started.

Principle of operation

A simplified schematic of the line-type pulse modulator with energy recovering deQing circuits is shown in Fig.1.

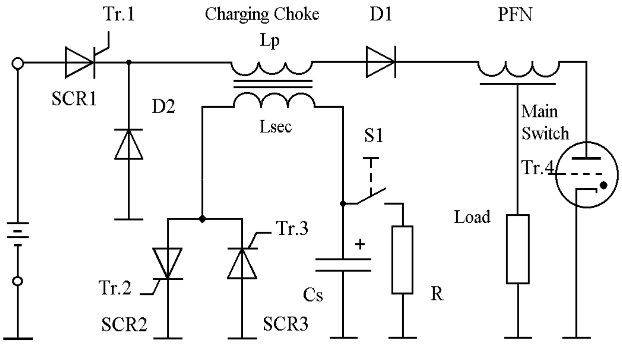

Fig. 1 A simplified schematic of the line-type modulator with energy recovering deQing circuit

The traditional portion of the scheme consists of the dc power supply, charging choke with deQing switch SCR3, storage capacitor C_s and resistor R, main charging diode D1, pulse forming network PFN and main switch (thyratron or SCR). The recovery components of the scheme are charging switch SCR1, recovery switch SCR2 and recovery charging diode D2. When the switch S1 is closed, the resistor R is connected in parallel to the storage capacitor C_s and the scheme works in the usual dissipative mode. In this case SCR1, SCR2 and D2 can be excluded from the scheme. The idea of energy recovering deQing is to transfer the energy that has been stored in the capacitor C_s during the deQing process of the current charging cycle directly to the PFN capacitors, before the following main charging cycle starts.

Fig.2 represents the waveforms along with the sequence of triggering pulses Tr1-Tr4 when the scheme runs at the energy recovering deQing mode. The main charging cycle begins at the moment $t=t_4$, when the charging switch SCR1 is fired. When PFN voltage reaches a predetermined level U_{PFNreg}, the deQing switch SCR3 will automatically be fired thus providing the PFN voltage regulation. At the moment of deQing $t=t_5$ the energy accumulated in the charging choke will start to flow into the storage capacitor bank C_s. The deQing energy accumulation will be finished at $t=t_7$.

The deQing energy recovering cycle can be made at any moment within the time interval t_1-t_4, after discharging the PFN to a load but before starting the following main charging cycle. The recovery cycle is started at $t=t_2$, when the recovery

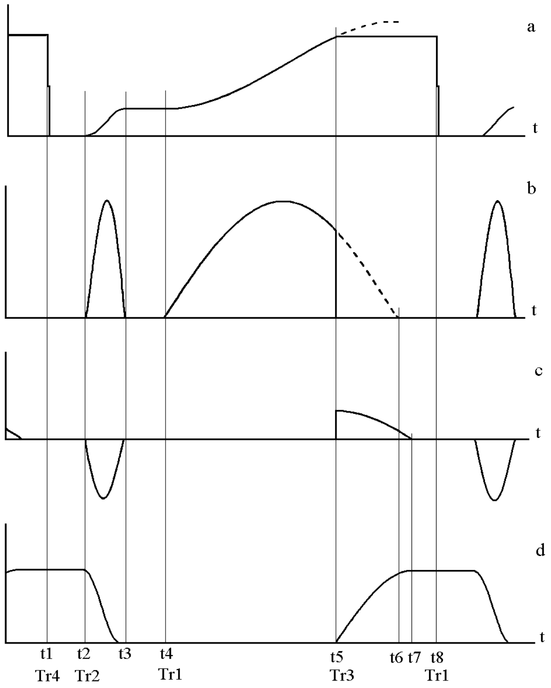

Fig. 2 Basic waveforms for recovery deQing mode
a - voltage across PFN capacitors
b - PFN capacitors charging current
c - current through storage capacitor C_s
d - voltage across storage capacitor C_s

switch SCR2 is fired. During the recovery process the energy accumulated in C_s will be flowing into the PFN capacitors, finally charging them to the voltage U_0.

PFN capacitors charging recovery current I_{rec} will flow through the recovery diode D2, charging choke primary L_p and main charging diode D1. For the main charging cycle the charging current flowing into the PFN capacitors and the resultant voltage across them are given, respectively, by

$$I_{PFN} = \frac{U_{eff}}{\rho} \sin \omega t \tag{1}$$

$$U_{PFN} = U_{eff} (1 - \cos \omega t) + U_0 \tag{2}$$

where $\omega = \sqrt{L_p C_{PFN}}$, $\rho = \sqrt{L_p / C_{PFN}}$, L_p is the inductance of the charging choke primary and C_{PFN} is the total PFN capacitance.

Assuming an ideal case when the whole deQing energy is transferred into the PFN energy and that the scheme is in steady-state conditions, the voltage U_0 can be expressed as follows

$$U_0 = I_0 \rho \tag{3}$$

where $I_0 = I_{PFN}(t_5)$ is the PFN capacitors charging current at the moment of deQing. For further calculations it is convenient to write the operating level of regulated PFN voltage as

$$U_{PFNreg} = 2 U_{DC} \alpha \tag{4}$$

where U_{DC} is the output voltage of the dc power supply, and α is a parameter, characterizing the level of deQing. Then the main parameters of the scheme can be expressed as presented below in Table 1.

Table 1

Parameter	Dissipative mode	Recovery mode
U_{eff}	U_{DC}	$U_{DC} - U_0$
$I_{\max}$	U_{DC}/ρ	$\frac{U_{DC}}{\rho}(1 - 2\alpha(1-\alpha))$
I_0	$2\frac{U_{DC}}{\rho}\sqrt{\alpha(1-\alpha)}$	$2\frac{U_{DC}}{\rho}\alpha(1-\alpha)$
$\sin \omega t_5$	$2\sqrt{\alpha(1-\alpha)}$	$\frac{2\alpha(1-\alpha)}{1-2\alpha(1-\alpha)}$
U_0	0	$2U_{DC}\alpha(1-\alpha)$
I_{av}	$2U_{DC} C_{PFN} PRR \alpha$ or $U_{PFNreg} C_{PFN} PRR$	$2U_{DC} C_{PFN} \alpha^2$ or $\frac{U_{PFNreg}^2}{2U_{DC}} C_{PFN} PRR$
$W_{L_p}(t_5)$	$2U_{DC}^2 C_{PFN} \alpha(1-\alpha)$	$\frac{1}{2} U_{DC}^2 C_{PFN} \sin^2 \omega t_5$

U_{eff} : effective charging voltage
$I_{\max}$: maximum PFN charging current
I_0 : PFN capacitors current at the moment of deQing
t_5 : moment of deQing
U_0 : PFN capacitors recovery voltage
I_{av} : average current from dc power supply
$W_{L_p}(t_5)$: deQing energy (stored in the charging choke at t_5)

The maximum relative amount of energy which can be saved at 100 % recovery efficiency, is equal to

$$\gamma = \frac{W_{L_p}(t_5)}{\frac{1}{PRR} I_{av} U_{DC}} = 1 - \alpha \tag{5}$$

where the numerator represents the deQing energy for dissipative mode, and the denominator equals to the amount of energy taken from the dc power supply over the entire charging period. An equivalent circuit describing the scheme during the processes of deQing and recovery (time intervals t_5-t_7 and t_2-t_3, correspondingly) is not finally clear up to now, so it was decided to build an experimental model of the scheme for investigation the idea of energy recovering deQing.

Experimental model

The Low Voltage Modulator Model (LVMM) parameters listed below

Maximum dc voltage : 300 V
Charging choke step-down ratio : 20 : 1
Primary inductance : 10 H
Secondary inductance : 25 mH
Total PFN capacitance : 1.2 μF
Storage capacitor bank : 300 μF

The LVMM total capacitance was chosen to obtain a characteristic charging impedance close to the one of real modulator. It provides an easy scaling of current flowing through the charging choke primary. LVMM has all the necessary electronics for firing the SCR switches as well as voltage dividers and current sensors for the most important signals.

Experimental results

Typical experimental pictures of the scheme's waveforms for dissipative and recovery modes are presented in Fig. 3a and 3b. Both pictures were made at U_{DC} = 275V and constant level of PFN regulated voltage, U_{PFNreg}.

The value of α can be defined by comparing the amplitude of the modulator output pulse with and without deQing and by measuring time interval t_5-t_6 (see Fig. 2) and then calculating α using the formulas for sinωt_5 given in Table 1. For both pictures the values of α defined by these methods were found to be 0.91 for the amplitude method and 0.90 for the time interval one. An efficiency of the energy recovering deQing can be found by comparing the average currents taken from the dc power supply in the dissipative mode $I_{av\ d}$ and recovery mode $I_{av\ r}$ as

$$\varepsilon = \frac{I_{avd} - I_{avr}}{\gamma I_{avd}} \qquad (6)$$

The experimentally measured values of efficiency were between 0.86 and 0.91, depending on α. For the real modulator a higher efficiency can be expected, due to the lower relative level of losses in switching devices.

Conclusion

The preliminary low-voltage investigation of the energy recovering deQing scheme shows that this scheme can be applied for any line-type pulse modulator with minimum additional expenses and efforts. Besides a reduction of the power consumption and elimination of the powerful deQing resistor along with it's air cooling system, it allows to increase the level of deQing and insures stable modulator output pulse over a wide range of the main ac voltage.

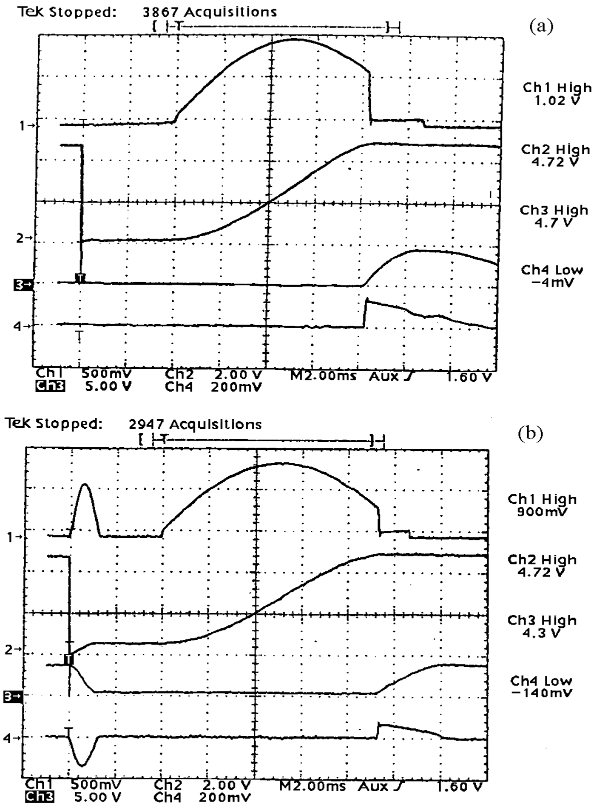

Fig. 3 Experimental waveforms for dissipative (a) and recovery (b) modes
Ch1 - PFN charging current, 10 V/A
Ch2 - PFN voltage, 1:100
Ch3 - storage capacitor voltage
Ch4 - storage capacitor current, 0.1 V/A

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References

[1] The Stanford Two-Mile Accelerator, ed. R. B. Neal, W. A. Benjamin, New York, 1968
[2] T. Shidara et all., Nucl. Instr. and Meth. A279 (1989) 423
[3] Energy Efficient DeQing for SLAC Klystron Modulators V. V. Nesterov, R. L. Cassel 9th Pulsed Power Conference, Albuquerque, New Mexico, 1993, SLAC - PUB - 6262
[4] Status of the S-Band Linear Collider Study, N. Holtkamp, DESY M - 93 - 05