A RESONANT CHARGING PULSED
HIGH VOLTAGE POWER SUPPLY

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1. **Summary**

The described H.V. Power Supply uses a 10 ms charging line for any H.V. capacity to be charged periodically. The repetition rate can, without difficulties, be increased till approximately 10 p.p.s.

The only H.V. element of the supply is its H.V. pulse transformer. All regulations are done on the low voltage side.

The amplitude stability for a constant charge-capacity is about 2% (thermal drift).

The H.V. output is short-circuit proof at any moment of the charging period. Special protection and interlock circuits are not necessary.

1.1. **Applications**

This type of Power Supply can only be used when the times of the discharge can be related to the Power Supply charge command signal by an interval of greater than 10 ms.

Using two independent low voltage-systems and a H.V. transformer with a double primary coil, positive and negative charge is possible, even with a different polarity from pulse to pulse. The polarity must, at least, be known 30 ms before charging.

If these application conditions are fulfilled, the pulsed H.V. supply is a cheap charging system.

For charging voltage below 10 kV and an energy per charge-pulse smaller than 20 joules it should not be used without reducing drastically the electronic steering system.

From 20 joules up to 300 joules charge energy, a single thyristor low voltage system, and from 300 joules ... 600 joules, a double thyristor system may be used.

From 600 joules upwards ignitors may be used instead of thyristors.

From 4000 joules upwards, the electromechanical forces in the primary circuit must be observed.

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1.2. Advantages

Compared with conventional Power Supply types, the greatest advantage is an electrically rigid construction; there is no direct voltage on the H.V. capacitive load (useful for series operation of capacitors for instance). When the system is switched off, the H.V. capacitor will be discharged automatically. There are no H.V. electronic elements in this supply. It will not produce X-rays.

The electronic steering system is small and the whole supply cheap.

A 200 joule - 45 kV supply can be placed in 3/4 of a rack, a 500 joule - 90 kV supply in 1 1/2 racks. The proper material costs were 2,500.- respectively 5,000.- SFr. To get the complete costs, working time included, one should multiply these values by 3.

2. Principle Functions and Circuit layout

2.1. Principle circuit

The principle circuit is shown in fig. 1:

- Electrolytic Capacitor
- Fast Impulse Switch Transformer
- Transformer Protection (T > 3 μsec)
- Cable or line to be charged. Capacity: C2
2.2. Function

First the capacitor $C_1$ must be charged to a voltage $u_1$ and the transformer should be pre-magnetized to allow a $\Delta\psi$ equal to twice the saturating flux

$$\Delta \psi = \psi_{pp} = 2 \psi_p = \int u dt$$

Both auxiliary circuits are not shown here.

When the fast switch (thyristor or ignitron) is fired, the primary voltage $u_p$ of the transformer jumps up to $u_1$ whilst the secondary voltage $u_s$ reaches the top voltage in half a period of a cosinus oscillation. (See fig. 2)

The primary and secondary current behave like half a sinus period.

The voltage $u_1$ of the primary capacitor drops from 100\% to 70\% of the charging voltage.

When the top voltage at the secondary capacitor $C_2$ is reached the current in the primary circuit goes through 0. The thyristor does not conduct inverse current, so the oscillation is stopped at the top voltage and immediate discharge will not happen.

The voltage will stay near the top voltage until the transformer saturates and discharges the capacitor $C_2$ by free non-linear oscillations.

The capacitor $C_2$ shall be discharged by another system before the transformer reaches saturation. (e.g. kicker magnet or spark chamber).

When the power supply is pushed to the limit of its capabilities, the ratio between flat top time and charging time becomes smaller and smaller. If it is overcharged, the thyristor may never stop conducting current till an auxiliary protection circuit breaks the current for a short moment.
Fig. 2

- $u_{c}$ (Capacitor low voltage)
- $u_{p}$ (Transformer, primary winding)
- $u_{s}$ (Transformer, secondary winding)
- $i_{p}$ (Primary current)
- $i_{s}$ (Secondary current)
2.3. Lay-out of circuit elements

First the charging voltage $u_2 \text{ch}$ for the load capacity $C_2$ must be given.

Secondary charging energy:

$$E_2 = \frac{C_2}{2} \frac{u_2^2}{2 \text{ch}}$$

Secondly the repetition rate and a convenient primary voltage shall be known.

We get a well optimised system (See fig. 1), when observing the following points:

2.3.1. The Primary Capacitor $C_1$

may be an electrolytic, surge proof type. It is better to drive many small capacitors in parallel than to have one large capacitor, because a small capacitor can normally be discharged faster than a big one.

The stored primary energy: $E_1 = \frac{C_1 u_1^2}{2 \text{ch}}$ is taken $E_1 = 2 E_2$

Reason: - Lower influence of primary capacity variations on secondary charging voltage due to temperature effects ($\approx 50\%$ only)
- Longer life of the electrolytic capacitors
- Better recharging efficiency in the low voltage system.
  ($60\% \ldots 80\%$ instead of $50\%$ when $E_1 = E_2$)

We find then:

$$C_1 = 2.5 \cdot r^2 \cdot C_2$$

(r = turns ratio of the transformer)

2.3.2. The primary switch

The circuit needs a unidirectional primary switch such as a thyristor or an ignitron. The available primary switch is the element which determines most the convenient primary voltage. A good value is e.g.

$$u_1 \text{ch} \quad 300 \ldots 450 \text{V}.$$  

In this case one can well operate a $600 \text{ V}$ - thyristor with $500/550 \text{ V}$ electrolytic capacitors for $C_1$.

When the H.V. system is earthed and the switch erroneously fired the primary current reaches about $210\%$ of the nominal value. (Oscillation between $C_1$ and $L_{1b}$ of the transformer) (See also 2.4)

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The nominal peak current for the switch must therefore be chosen as:

\[ J_{\text{nom}} \leq 0.48 J_{\text{surge}} \]

As a rough indication we may take:

1. Siemens thyristor BSTN 02-60 till \( E_2 = 200 \) joules
2. Parallel thyristors BSTN 02-60 till \( E_2 = 400 \) joules

When three or more thyristors are needed it is better to use one ignitron which can be driven by a medium power thyristor.

2.3.3. The H.V.-Transformer

is the most critical element of the circuit. It seems reasonable to use normal 50 Hz -H.V. Transformers. The charging times then become about 5 ... 15 ms and the primary currents stay in reasonable order of magnitude.

In this application the nominal 50 Hz power of the transformer is defined as follows:

- the inductive primary voltage at nominal current and secondary short circuit is \( \leq 5\% \) of nominal voltage.
- the resistance losses shall be smaller than \( 3\% \).
- the nominal voltage \( U_r \) must be defined so that the transformer does not saturate at \( U \leq 1.30 U_n \).

All calculations are made in order that the transformer will need its nominal flux during the charging time and the difference between saturation and nominal flux is left available for the flat top. So the flat top at nominal conditions reaches 15\% ... 20\% of the charging time. Using an over dimensioned' transformer, the ratio of flat top to charging time becomes more favourable, but possibly the primary switch must stand higher currents.

- The insulation level may be chosen so that the nominal 50 Hz rms voltage is 60\% of the nominal charge voltage.
- The turns ratio \( r = \frac{N_2}{N_1} \) (\( N \): number of spires primary/secondary) is chosen

\[ r = 0.96 \cdot \frac{u_2}{u_1} \]

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The nominal power shall be

$$S_n = 12s^{-1} \cdot E_2$$

(Under this condition, the power supply will really reach a minimum flat top of 15\% of the charging time).

\[ e.g. \quad S_n \begin{align*} &1200 \text{ VA when } E_2 = 100 \text{ joules} \\ &5 \text{ kVA when } E_2 = 410 \text{ joules} \\ &240 \text{ kVA when } E_2 = 20 \text{ k-joules} \end{align*} \]

- The transformer is designed in this chapter for nominal operation.

If, for testing equipment a higher voltage than nominal voltage is required, this may be obtained, when the secondary charge capacity \( C_2 \) is reduced.

Reducing drastically \( C_2 \) and keeping \( u_1 \text{ ch} \) constant, one can at maximum increase \( u_2 \) at 170\%.

Reducing \( C_2 \) at 50\% and increasing \( u_1 \text{ ch} \) at 130\% one may get an increase of \( u_2 \) till 150\%.

- For flux calculation in the transformer, one may count during the charging time \( T \) under nominal conditions a flux in the iron correspondent to the product.

$$\psi_2 = 0,64 \cdot T \cdot u_2 \text{ charge}$$

(For an ideal transformer without any resistive losses, the factor would be 0,50. The integral \( \int_0^T u_2 (t) \text{ d}t \) would lead to a value of about \( \psi_2 = 0,56 T \cdot u_2 \text{ ch} \) whilst the integral \( \int_0^T u_1 (t) \text{ d}t \) would lead to about \( \psi_2 = 0,70 T \cdot u_2 \text{ ch} \). The differences between these four factors are due to the damped half oscillation of the charging period and to the resistive voltage losses in the primary and secondary windings of the transformer).

- The remagnetisation current through the transformer shall at least be equal to twice the peak value of the 50 Hz magnetisation current at nominal voltage.

2.3.4. Transformer protection circuit \( R_3 C_3 \)

The transformer must be protected against nanosecond kicks, when charging a thyristor or spark gap circuit.

The time constant \( \tau = R_3 C_3 \approx 4 \mu \text{sec} \) is sufficient for 50 Hz HV transformers. The resistor \( R_3 \) shall be smaller than 50\% of the secondary copper resistance.

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2.4. Characteristic impedance, charging time and peak values of currents

From fig. 1 we derive a primary replacing circuit:

Fig. 3a

\[ L \quad \frac{C_1}{u_{ich}} \]

\[ c_2' = c_2 \cdot r^2 \]

\[ c_3 \ll c_2, \text{ negligible,} \quad c_2' = 0.4 \cdot c_1 \]

Fig. 3b

\[ \frac{C_2'}{u_{ich}} \]

\[ 0.7 \cdot C_2' \]
2.4.1. Characteristic Impedance

\[ Z_0 = \sqrt{\frac{L_{\sigma_1}}{0.71 C_2^1}} \]

2.4.2. Charge time

\[ T_{ch} = \pi \sqrt{\frac{L_{\sigma_1} \cdot 0.71 C_2^1}{L_{\sigma_1} C_2^1}} = 2.65 \sqrt{\frac{L_{\sigma_1} C_2^1}{L_{\sigma_1} C_2^1}} \]

Under normal conditions with a 50 Hz transformer, the charge time will be about 10 ms.

2.4.3. Primary nominal peak current

\[ J_1 \approx \pi \cdot c_2^2 \cdot \frac{U_{2ch}}{r} \cdot \frac{1}{T_{ch}} \approx 0.6 \frac{U_{1ch}}{Z_c} \]

2.4.4. Primary Short Circuit Peak Current

\[ \hat{J}_1 \approx 0.3 \frac{U_{1ch}}{\sqrt{L_{\sigma_1}/C_1}} \approx 2.1 \hat{J}_1 \]

\[ \hat{J}_{1c} < \frac{U_{1ch}}{\sqrt{L_{\sigma_1}/C_1}} \]

when no resistance losses in transformer are considered
3. **An Example of a 45 kV-100 joule unit**

Fig. 4 shows the complete Block-Diagram: the recharging current for the low voltage storage capacitor (\( \approx 2 \) F) flows in the inverse sense through the primary coil of the H.V. transformer. When the charge regulator (4) stops the charging of the capacitor, 1A remains on the primary coil of the transformer to keep it premagnetised. (flowing back to the dc. supply at 450V).

When the higher circuit (3) fires the main thyristor BSTN 02-60 the charging circuit (2) with the BTY 87-600 will interrupt the charging current for 10 ms to give a better flat top.

Immediately after each charging pulse the system (2) gets the BTY 87-600 continuously conducting again. The relay (1) opens the current circuit, when the main thyristor accidentally does not stop conducting. (e.g. when the supply is shorted on the H.V. output or if a H.V. break-down happens before the flat top is reached).

The relay (5) discharges the storage capacitor, when the 220 V line is interrupted.

The H.V. transformer is largely overdimensioned. (1.1 kVA would be sufficient in this case).

With a few modifications in capacitors and resistors this supply may be improved till 300 joules per pulse.

A circuit of the same principle with two thyristors BSTN (02-60) and a stronger transformer has been built for 600 joules and 90 kV.
Fig. 5a/5b show the H.V. at a 1% connection of the transformer and the current at 1Ω during a charging pulse.

Load capacity $C_2 = 115$ nF

energy $E_2 = 117$ joule at 45 kV

fig. 5a/5b charge at 41 kV

5b damped non linear oscillations

fig. 5c increasing flat top time with decreasing voltage

More detailed circuits are available for those interested.
Fig. 5a
10 kV/div
1 ms/div
50 A primary/div
or 0.5 A secondary/div

Fig. 5b
20 kV/div
5 ms/div
100 A primary/div
1 A secondary/div
or 1 A secondary/div

Fig. 5c
20 kV/div
1 ms/div
increasing flat top with decreasing voltage