CONFIGURATIONS AND APPLICATIONS OF SATURABLE PULSE TRANSFORMERS IN HIGH POWER PULSE MODULATION*

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Abstract

In this paper, saturable pulse transformers (SPTs) based on multiple batches of windings in parallel combination and coaxial cylindrical conductors are presented. The proposed SPT can be employed as the transformer and magnetic switch simultaneously for pulse capacitor or high-voltage pulse modulator of several hundred kV range. The SPT which has important features such as auto-resetting of core, high step-up ratio and low saturation inductance, achieves a compact integration of common transformer and magnetic switch. The proposed SPTs were applied in a high power pulse modulator based on a helical Blumlein pulse forming line (HBPFL). When the SPT played as a pulse transformer, the HBPFL can be charged to 200 kV. When the SPT played as a main magnetic switch of the HBPFL, it helped to form a quasi-square voltage pulse with amplitude of 180 kV，pulse duration of 130 ns, rise time of 60 ns. Furthermore, important applications of SPT in 100kV-range compact Marx generator and ns-range synchronization of multiple high-voltage pulses are proposed and demonstrated.

Compact high power pulse modulator with high repetition rate and long life time has hot applications in defense, industrial, agriculture, environmental protection, medical care, bio-electronics, and so on. Voltage transformation and switch are crucial in pulse modulator. Saturable pulse transformer (SPT) is a compact integration device which combines the functions of the independent pulse transformer and magnetic switch [1,2]. Through the transition from the unsaturated state to the saturated state of core, the secondary windings of SPT can operate at transformer mode and magnetic switch mode in order. As the volume and cost of the magnetic core are decreased, the SPT shows promising applications in high-power pulse modulator. However, when the working voltage is higher than dozens of kV, the common SPT can not obtain high step-up ratio and low saturation inductance (<1 μH) simultaneously, due to the large size of the magnetic core and windings [2,3]. This difficulty hinders further applications of a common SPT.

In order to provide possible solutions to the difficulty aforementioned, SPTs based on multiple batches of windings in parallel combination and coaxial cylindrical winding configuration are both introduced. In the SPT, The physical suppression effect caused by reversed magnetic coupling mechanism among primary and secondary windings [4] can reduce the saturation inductance of the SPT windings to a level lower than their structure inductances, which helps to achieve a magnetic switch with low saturation inductance. Traditional spark gap can be substituted by the proposed SPT. This paper explores and demonstrates a pulse modulator in which the proposed SPT plays as the charging transformer and discharging magnetic switch of a helical Blumlein pulse forming line (HBPFL). In addition, important applications of the SPT in compact integrated Marx generator and high-voltage ns-range synchronization of multiple pulses are also introduced.

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CONFIGURATION CONSIDERATIONS OF SPT AND APPLICATION IN PULSE MODULATOR SYSTEM

SPT Configuration Based on Multiple Batches of Windings in Parallel Combination

The introduced new SPT consists of the magnetic core, primary windings and secondary windings. As Fig. 1 shows, the magnetic core consists of m piles (m=6) of magnetic toroids stacked along the axial direction. The primary windings of SPT are formed by 6 batches of primary sub-windings in a parallel combination, and each sub-winding is formed by a curled copper tape which has only one turn. As shown in Fig. 1, the first primary sub-winding goes across the top of the first magnetic toroid, goes down to the bottom, and finally goes out across the bottom of the first magnetic toroid. The 6 batches of primary sub-windings almost have the same characteristic parameters. The equivalent turn number of the entire primary windings of the SPT is as Np=1/m=1/6.

The secondary windings contain s batches (s=12) of sub-windings along the azimuthal direction of the magnetic core can be separate or in a parallel combination. Every secondary sub-winding with the same turn number as Ns (4.75) has a uniform coil distribution along the azimuthal direction. As all the s batches of the secondary sub-windings in parallel combination share the same primary windings as shown in Fig. 1, the proposed SPT with new configuration has a step-up ratio as (1/m): Ns=1:28.5. After the magnetic core saturates, the strong magnetic coupling effects between the primary and secondary windings disappear. The secondary sub-windings of the SPT play as a magnetic switch which controls the discharge course of the secondary circuit of the SPT. The parallel combination structures of the multiple SPT windings ensure the properties such as high step-up ratio and low saturation inductance of the SPT [5].

In conclusion, in contrast to a common SPT, the proposed SPT can decrease the saturable winding inductance by an order of magnitude, and the compact integration of independent pulse transformer and magnetic switch is really achieved [5].

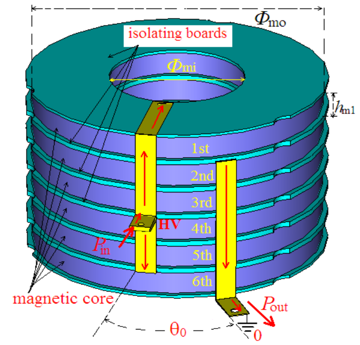


Figure 1: Assembly proposed SPT structure of the *m* batches of primary sub-windings and the *m* batches of magnetic core.

SPT Based on Coaxial Cylindrical Winding Configuration

As we know, coaxial cylindrical conductors have low structural inductance. In this section, the coaxial cylindrical winding configuration is introduced to construct SPT. The proposed mutual-coupling SPT with coaxial cylindrical structure mainly consists of the magnetic core, the primary windings and the secondary windings with coaxial cylindrical conductors.

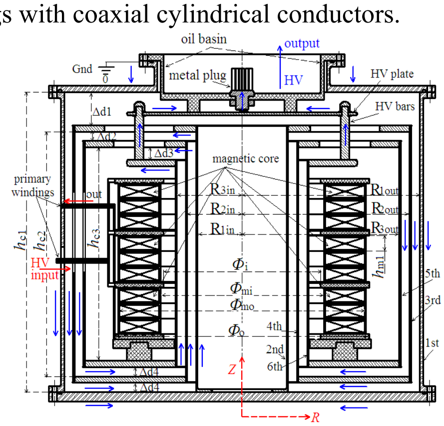


Figure 2: Geometric structure of the proposed SPT with cylindrical coaxial conductors.

The input port of the primary windings can withstand high-voltage pulses ranging from 20 to 30 kV. The proposed SPT shown in Fig. 2 has a step-up ratio of (1/3):3=1:9. Two important features of the proposed SPT are as follows. Firstly, after the magnetic core saturates, the secondary windings of SPT has low saturable structural inductance, as coaxial cylindrical conductors are employed; the reversed suppression effect of mutual inductance between the primary and secondary windings is still the crucial mechanism which decreases the total saturable inductance to a level lower than the saturable structural inductance. Secondly, the coaxial cylindrical conductors allow high-voltage endurance of SPT at several hundred kV range [4].

High-voltage Pulse Modulator Based on the Proposed SPTs and HBPFL

One of the most important applications of the proposed SPT in this paper is that the SPT plays as the step-up transformer and discharging magnetic switch of the pulse modulator system based on HBPFL. As the traditional spark gap playing as the main switch is substituted by the proposed SPT, the modulator system can achieve a more compact structure and longer life time.

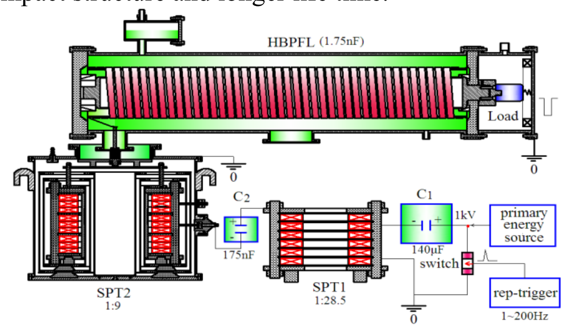
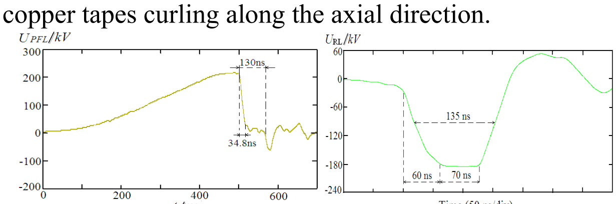


Figure 3: The structure of the produced high-voltage pulse modulator system based on a HBPFL and two stages of SPT units in series.

A high-voltage pulse modulator based on a HBPFL and two stages of SPT modulation units in series was produced. The modulator structure is shown in Fig. 3. The modulator system consists of a primary energy source, a vacuum trigger switch, the first SPT modulation unit (C_1~SPT1~C_2), the second SPT modulation unit (C_2~SPT2~HBPFL), a matched dummy load R_L and measurement system. SPT1 and SPT2 are shown in Fig. 1 and Fig. 2 respectively. Both of the two SPT modulation units satisfy the dual-resonance condition of pulse transformer. As shown in Fig. 3(a), the HBPFL consists of three coaxial cylindrical conductors such as the inner cylindrical conductor, the tape-helix cylinder, and the outer cylindrical conductor. The tape helix is formed by copper tapes curling along the axial direction.



(a) (b)

Figure 4: (a) The charge voltage waveform of the HBPFL; (b) The typical voltage waveform on the 160 Ω load.

In the single-shot mode experiment, C_1 was charged to 1.6 kV, and the voltage of the primary windings of SPT2 was tested as 21 kV. SF_6 gas (2.3 atm) filled in SPT2 to keep insulation. The charge voltage pulse U_{PFL} of HBPFL is shown in Fig. 4(b). The maximum charge voltage of HBPFL was about 215 kV. After the core of SPT2

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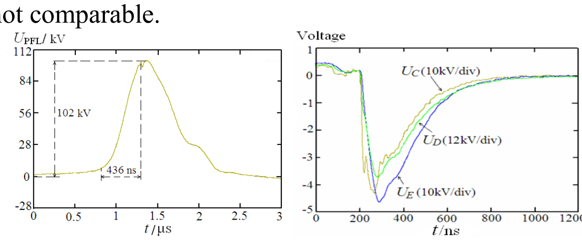
saturated, the fall time of pulse U_{PFL} was about 34.8 ns. The load voltage pulse U_{Load} was obtained as shown in Fig. 4(c). The rise time, full width at half maximum (FWHM), flat top time and amplitude of U_{Load} were 60 ns, 135 ns, 70 ns and 180 kV respectively. According to the formula $t_r=\pi(L_{ss}C_{B2})^{1/2}$, the saturated inductance L_{ss} of SPT2 was calculated as 417 nH. Experimental results demonstrated that SPT played as the charging transformer and discharging magnetic switch of the HBPFL in high-voltage pulse modulator was feasible.

APPLICATIONS IN THE COMPACT SOLID-STATE MARX GENERATOR AND NS-RANGE SYNCHRONIZATION

A solid-state Marx generator is introduced in which traditional spark gaps are substituted by the proposed SPT shown in Fig. 1. Through the transition from the unsaturated state to the saturated state of magnetic core of SPT, multiple stages of Marx capacitors can be synchronously charged in parallel and synchronously discharge in series. The basic working principles of the Q-stage solid-state Marx generator are demonstrated in reference [6]. A 3-stage solid-state Marx generator based on SPT was produced. The HBPFL shown in Fig. 3 played as the load capacitor of the Marx generator in experiment. When the primary charging capacitor was charged about 1 kV, each stage of Marx capacitor C_q was charged about 22~25 kV. The charging voltage pulse U_{PFL} of HBPFL is presented in Fig. 5(a). The peak voltage and rise time of U_{PFL} were 102 kV and 436 ns. The step-up ratio of the produced 3-stage Marx generator achieved 1:102, to which a traditional 3-stage Marx generator was not comparable.



(a) (b)

Figure 5: (a) The voltage waveform of the HBPFL playing as the load of the new 3-stage Marx generator; (b) The tested 3 high-voltage synchronous pulses in experiment when the charge voltage of the SPT was high.

We explored the multiple-pulse synchronization based on a communal magnetic switch in reference [7], and experimental results demonstrated that the error of multiple-pulse synchronization was less than 5 ns. The SPT synchronization technology has advantages of easy controlling and full automaticity. Traditional spark gaps are substituted by the proposed SPT which is similar to the structure shown in Fig. 1, but all batches of secondary windings were in parallel combination. Hence, it is promising to improve the synchronization error and life time of the synchronization system. Experimental system for 3-pulse synchronization based on SPT was established, and the three load voltage pulses U_C~U_E are presented in Fig. 5(b).

CONCLUSIONS

In this paper, SPTs based on multiple batches of windings in parallel combination and coaxial cylindrical conductors are presented. The proposed SPT can be employed as the transformer and magnetic switch simultaneously for pulse capacitor or high-voltage pulse modulator of several hundred kV range. The SPT which has important features such as auto-resetting of core, high step-up ratio and low saturation inductance, achieves a compact integration of common transformer and magnetic switch. In the SPT, The physical suppression effect caused by reversed magnetic coupling mechanism among primary and secondary windings can reduce the saturation inductance of the SPT windings to a level lower than their structure inductances, which helps to achieve a magnetic switch with low saturation inductance. The proposed SPTs were applied in a high power pulse modulator based on a helical Blumlein pulse forming line (HBPFL). When the SPT played as a pulse transformer, the HBPFL can be charged to 200 kV. When the SPT played as a main magnetic switch of the HBPFL, it helped to form a quasi-square voltage pulse with amplitude of 180 kV, pulse duration of 130 ns, rise time of 60 ns. A 100kV-rang ultra-compact integrated Marx generator based on SPT is introduced. Important application of SPT in ns-range synchronization of multiple high-voltage pulses are proposed and demonstrated.

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