Experiment No.14: Study of ZVS active-clamped Forward Converter with synchronous rectifier
A Novel Transient Current Build-up Technique for a ZVS PWM Active Clamped Forward Converter with Synchronous Rectifier

ABSTRACT: The objective of this paper is to propose a novel transient current build-up technique that enables soft switching of all the switching devices of an active-clamped forward converter with synchronous rectifier. The circuit configuration, shown in Fig.1, of the proposed forward converter is simple. It does not require a magnetic amplifier - that is used by a few forward converter topologies at the secondary side of the transformer to ensure ZVS of the main switch. Another comparable method [1], which uses synchronous rectifier for transient current build-up to enable ZVS of the main switch, does not eliminate the switching loss of the synchronous rectifier completely. This topology produces less voltage stress across the devices.

INTRODUCTION: In the proposed forward converter a tertiary winding is used along with an auxiliary switch for transient current build-up that enables ZVS of the main switch. The auxiliary switch itself undergoes ZCS. The active clamp switch at the primary of the transformer turns on and off under ZVS. The switches of the synchronous rectifier operate under ZVS condition. Analysis and experimental results of the proposed active-clamp forward converter is presented for a 48 V input, 5 V- 60 watt output switched at 100 kHz.

CIRCUIT ANALYSIS: In the following analysis all the switching devices and the passive components are considered to be ideal. The leakage inductance of the primary is included in \( L_r \). The circuit waveforms of the proposed converter are shown in Fig. 2. It also defines different modes of operation, namely Mode 1 to Mode 9. The equivalent circuits of these modes are shown in Fig. 3(a) to Fig. 3(i).

Mode 1: This is the standard on state of the active-clamped forward converter. In this mode \( S_2 \) and \( SR_1 \) are on and \( S_1 \) and \( SR_3 \) are off. The primary current \( i_{L_r}(t) \) is given by \( i_{L_r}(t) = i_{s_1}(t) = \frac{i_{L_p}(t)}{n} + i_{L_m}(t) \), where,

\[
i_{L_m}(t) = i_{L_m}(t_0) + \frac{V_S}{L_m + L_p} \cdot t
\]

At the end of this period \( i_{L_r}(t) = i_{L_r}(t_f) \). This mode ends when \( S_1 \) is turned off.
Mode 6: In this mode the auxiliary switch $S_3$ is on. $S_2$ and SR2 are also on. Since $V_{pri} = 0$, the transient current builds-up in the primary in the appropriate direction for subsequent ZVS turn-on of $S_1$. \[rac{di_{Lr}}{dt} = -V_c.\]

The reflected current flows in the tertiary winding, \[i_{ter} = i_{Lr} \times n_1,\] where $n_1$ is the turns ratio between primary winding and tertiary winding. The voltage across SR1 falls towards zero in a resonant circuit where $L_{sh}$ and $C_{out}$ (the output capacitor of SR1) act as resonant elements. This mode ends when $S_2$ is turned off.

Mode 7: This mode begins with the turn-off of $S_2$ under ZVS. In this mode only $S_3$ and SR2 are on. $V_{pri} = 0$. Since \[\frac{di_{Lh}}{dt} = 0\] and \[i_{Lh}(t_6) = 0,\] therefore \[i(t) = 0\] and \[i_{SR2}(t) = i_{LD}.\] In the tertiary winding \[i_{ter}(t) = i_{Lr}(t) \times n_1.\] In the primary a resonant circuit is formed with $L_r$, $C_1$ and $C_2$. The equations are

\[i_{Lr}(t) = i_{Lr}(t_6) \cos\left(\sqrt{\frac{1}{L_r \left(C_1 + C_2\right)}}t\right)\] and \[V_{S2} = i_{Lr}(t_6) \sqrt{\frac{L_r}{C_1 + C_2}} \sin\left(\sqrt{\frac{1}{L_r \left(C_1 + C_2\right)}}t\right).\] This mode ends when $V_{s1}(t_7) = 0$ and $V_{S2}(t_7) = V_z + V_C$. Mode 8: In this mode $S_3$ and SR2 continue to be on, and in the primary the body diode of $S_3$ also conducts. $V_{pri} = 0$, $V_{s1}(t) = 0$, $V_{s2}(t) = V_z + V_C$. The primary current slope
Mode 2: This mode begins when $S_1$ is turned-off. SR4 is still on and $S_2$, $S_3$ and SR2 are off. The capacitors $C_1$ and $C_2$ are charged and discharged by constant current $i_{2r}(t_1)$ and therefore turn-off of $S_1$ satisfies ZVS:

$$C_1 \frac{dV_{S1}}{dt} - C_2 \frac{dV_{S2}}{dt} = i_{1r}(t_1).$$

This mode ends when $V_{S1}(t_2) = V_g$ and $V_{S2}(t_2) = V_c$. The primary voltage is given by $V_{pri} = V_g - V_{S1}$, therefore $V_{pri}(t_2) = 0$ when $V_{S1} = V_g$ and this implies that $V_{SR2}(t_2) = \frac{V_{pri}}{n} - L_{sh} \frac{di_{kh}}{dt} = 0$ and anti-parallel body diode of SR2 will start to conduct.

Therefore any turn-on of SR2 after this will be ZVS.

Mode 3: In this mode the capacitors $C_1$ and $C_2$ continue to charge and discharge in the same linear rate till $V_{S1}(t_3) = V_g + V_c$ and $V_{S2}(t_3) = 0$. This mode ends when $S_2$ and SR2 are turned-on together. In the secondary side both SR1 and the body diode of SR2 are under conduction. Since $V_{pri} < 0$, $\frac{di_{kh}}{dt} < 0$; however duration of this mode being very small there is hardly any change in $i_{kh}$.

Mode 4: This mode starts when $S_2$ and SR2 are turned-on together, SR1 is still on. It may be noted that both the devices turn-on under ZVS; additionally SR2 turn-on under ZCS. This mode ends when the commutation is complete, that is $i_{SR1}(t_4) = 0$ and $i_{SR2}(t_4) = i_{L_0}$, and SR1 is turned off under ZCS. At the end of this period the primary side current has only magnetizing current component and the load component is zero: $i_{Lr}(t_4) = i_{Lm}(t_4)$.

Mode 5: This is the standard off state of the active-clamped forward converter where only $S_2$ and SR2 are on and the voltage across primary is clamped to $V_c$. This mode ends when the auxiliary switch $S_3$ is turned on.
is given by \( \frac{di_{Lp}}{dt} = V_g \). This mode ends when the primary current reaches magnetizing current level, \( i_{Lp}(t_s) = i_{Lm}(t_s) \). At that time current in the tertiary winding is zero, \( i_{tr}(t_s) = 0 \). Note that the subsequent turn off of \( S_1 \) would be ZCS. The subsequent turn on of \( S_1 \) is ZVS, if we ignore the magnetizing current, and the subsequent turn on of \( SR_1 \) is also ZVS. The turn off of \( SR_2 \) is ZVS as current transfers to the body diode. If this mode is extended beyond \( i_{tr}(t_s) = 0 \), state then \( i_{Lp}(t_s) = 0 \), and then the continuity of the magnetizing current is maintained at the secondary side through the conduction of the body diode of \( SR_1 \). Mode 9: This mode starts with the turn on of \( S_1 \) and \( SR_1 \) along with turn off of \( S_3 \) and \( SR_2 \) at the same time. The body diode of \( SR_2 \) conducts. However since, \( V_{pot} = V_g \), \( \frac{di_{Lp}}{dt} = \frac{V_g}{L_{ke}} \), the current increases in \( SR_1 \) and decreases in \( SR_2 \). This mode ends when \( i_{SR_1}(t_g) = 0 \) and converter enters the initial state of Mode 1.

**EXPERIMENTAL RESULTS:** The experimental results of the prototype converter...
are presented in Fig. 4. The operating condition is: input 48 V, output 5 V, output power 60 watt, and switching frequency is 100 kHz. The component values are $L_r = 4\mu H; C_1 = C_2 = 3.3mF; n_p : n_s : n_T = 32 : 20 : 32; C_C = 680mF$

Fig. 4 Experimental results of the proposed active clamp ZVS forward converter with synchronous rectifier.
PROCEDURE:

Step 1: Make the control circuit in the bread board to generate gate pulses for all the five switches.

Step 2: Connect the corresponding points of PCB with the bread board.

Step 3: Connect the power circuit and the load rheostat.

Step 4: First turn on the control circuit and then the power circuit.

Step 5: Save the following waveforms:

1) All the gate pulses in different combinations
2) $V_{DS}$ of $M_1$ and gate pulse of $M_1$
3) $V_{DS}$ of $M_5$ and gate pulse of $M_5$
4) $V_{DS}$ of $M_4$ and gate pulse of $M_4$
5) $V_{DS}$ of $M_3$ and gate pulse of $M_3$
6) Voltage across $R_t$ (current through tertiary) and gate pulse of $M_2$
7) Voltage across $R_9$ (current through $M_3$) and gate pulse of $M_3$
8) Voltage across $R_{11}$ (current through primary) and voltage across $R_t$ (current through tertiary)

Step 6: Turn off the power circuit and then the control circuit.
Power Circuit
Gate Driver Circuit
Control Circuit (part2)