High Voltage DC Power Supply Topology for Pulsed Load Applications with Converter Switching Synchronized to Load Pulses

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***Abstract* - High voltage power supplies for radar applications are investigated, which are subjected to pulsed load (125 kHz and 10% duty cycle) with stringent specifications (<0.01% regulation, efficiency>85%, droop<0.5V/micro-sec.). As good regulation and stable operation requires the converter to be switched at much higher frequency than the pulse load frequency, transformer poses serious problems of insulation failure and higher losses. This paper proposes a methodology to tackle the problems associated with this type of application. Synchronization of converter switching with load pulses enables the converter to switch at half the load switching frequency. Low switching frequency helps in ensuring safety of HV transformer insulation and reduction of losses due to skin & proximity effect. Phase-modulated series resonant converter with ZVS is used as the power converter.**

Keywords – **HV Power supply, phase modulation, ZVS, pulsed load.**

I. INTRODUCTION

High voltage (HV) power supplies are used in industrial, medical, and air borne applications [1], [2], [4]. In many high-power, high-voltage applications such as TWT, laser based systems, X-ray equipment, radar power supplies, high quality power is required. In addition, radar power supplies are subjected to pulsed load.

HV transformer is a crucial element in HV power converters due to large no. of secondary turns and insulation requirements, which exacerbate its non-idealities like winding capacitance and leakage inductance. Attempts have been made to absorb these non-idealities as useful elements. It has resulted in series, parallel, and series-parallel resonant converters (i.e., SRC, PRC, & SPRC respectively) with their own advantages and disadvantages. These can be controlled either by frequency modulation or constant frequency phase-modulation [6],[7]. Phase modulation is generally preferred due to constant switching operation, which yields optimum design of reactive elements. Phase modulated resonant converter, equivalent ckt. of the HV transformer and various resonant tank circuits are shown in figs.1, 2 and 3 respectively.

The SRC is free from possible saturation of HV transformer and allows capacitive filter at the output. It absorbs the leakage inductance of the HV transformer. It gives high efficiency over a wide range of load. Though transformer winding capacitance is not absorbed in the tank ckt., SRC has been used in the high-voltage, high-power converters due to several other advantages.

The PRC absorbs the winding capacitance into the resonant tank ckt. But it requires an LC filter at the output, which is prohibitive due to size constraint. It has been shown in [3] that it is possible to remove this component without degrading the performance. Even then the PRC has the limitations like, transformer saturation in full bridge topology and low efficiency at light loads.

The SPRC combines the advantages of both SRC & PRC. The output is controllable for no-load or light-loads, and the light load efficiency is high. In [5], it has been proposed for pulsed load application. It absorbs all the parasites of the HV transformer. But the hybrid converters are complex to analyze and difficult to control.

Radar power supplies are subjected to pulsed load with high pulse repetition frequency (PRF). Table I and fig.4 describe the specifications used for the prototype. Actual application requires an output voltage and power level of 22kV and 1.25kW. As the load switches at high frequency, the converter needs to be switched at one order of magnitude higher than load switching frequency for good regulation and stable operation. Tackling high frequency, high voltage, high power and tight regulation in one power converter is a challenging issue. The combination of "high power & high frequency inverter" and "high frequency & high voltage transformer" is critical resulting in number of compromises in terms of output regulation, response time, etc. The problems encountered in general with high voltage and high frequency transformer are: 1) Insulation failure, 2) Skin & proximity effect resulting in increased copper losses and temperature rise, 3) Increased iron losses, 4) Parasites of HV transformer i.e., leakage reactance results in poor regulation and secondary winding capacitance results in current spikes and delay.

This paper presents a control technique for high-voltage DC power supplies subjected to pulsed loads with stringent performance specifications demanding tight output voltage regulation and high efficiency. The above-mentioned problems with this type of application can be tackled by switching the power converter in synchronism with the pulsed load. It results in converter switching frequency equal to half the load switching frequency. It reduces the stress on the insulation of the HV transformer, reduces the losses and synchronized switching helps in achieving good regulation and elimination of beat frequency oscillations in the output voltage.

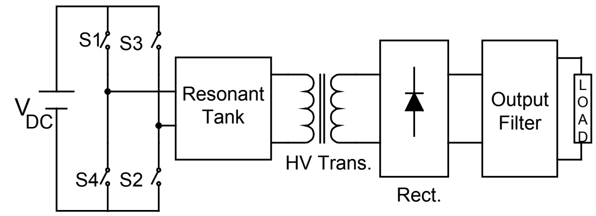


Fig. 1

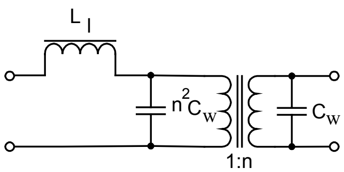


Fig. 2

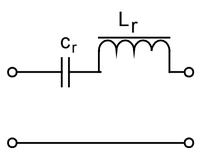


Fig. 3 (a)

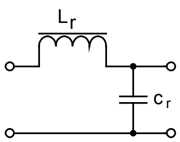


Fig. 3 (b)

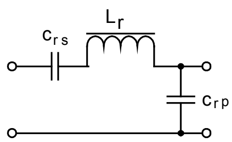


Fig. 3 (c)

TABLE I

Supply Voltage: 270 VDC ± 10 %	Regulation: < 0.01 %
Output Voltage: 1KV	Droop: 0.5V/ μ sec.
Peak Power: 6 KW	Load Switching Freq.: 125 kHZ
Average Power: 600 W	Efficiency: > 85 %

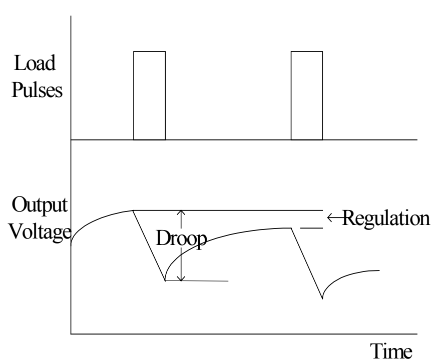
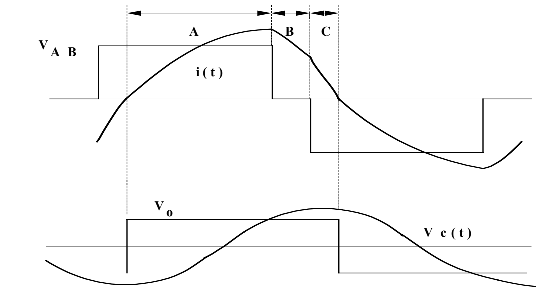


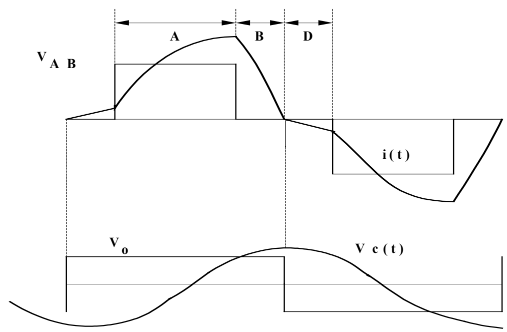
Fig. 4

II. PHASE-MODULATED SERIES RESONANT CONVERTER

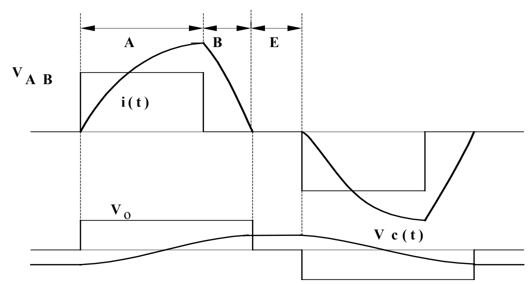
Phase-modulated series resonant converter (PM-SRC) is suitable for high-voltage DC power supplies. The converter switches at a frequency slightly higher than the resonant frequency of the tank circuit, facilitating ZVS of the devices with the aid of the capacitors connected across them. PM-SRC operates in three modes, namely, mode-1, mode-2, and mode-3. The relevant waveforms of the tank current, $i(t)$, inverter output voltage, v_{AB}, resonant capacitor voltage, $v_c(t)$, and output voltage, V_o, under the



(a) Mode-1 operation



(b) Mode- 2 operation



(c) Mode -3 operation

Fig. 5. Waveforms of PM-SRC

three modes are shown in fig.5. The various sub-periods are shown as A, B, C, D, and E. The general equations describing the LC tank circuit with excitation $(V_{in} - V_{out})$ are given by

$$i(t) = I(0)\cos\omega_r t + \frac{[(V_{in} - V_{out}) - V_c(0)]}{Z_c}\sin\omega_r t \qquad (1)$$

$$v_c(t) = -[(V_{in} - V_{out}) - V_c(0)]\cos\omega_r t + Z_c I(0)\sin\omega_r t + (V_{in} - V_{out}) \quad (2)$$

$I(0)$ and $V_c(0)$ are initial values of $i(t)$ and $V_c(t)$ respectively. Z_c is the characteristic impedance of the LC ckt., and ω_r is the resonant frequency. Current and voltage equations for each of the sub-period in different intervals are obtained by substituting the appropriate values of input voltage, output voltage and initial conditions in the above equations.

III. PROPOSED CONTROL TECHNIQUE

Control of HV power supplies under pulsed loading is considered. Load pulses have constant frequency and duty cycle. The load can be considered as current pulses of constant magnitude. During the interval of loading, variation in the load current magnitude is negligible. Each load pulse takes certain amount of charge from the output capacitor. For maintaining good output voltage regulation, the charge on the output filter capacitor needs to be replenished after the occurrence of every load pulse. As the load switches at very high frequency, the converter should switch at least at a frequency of one order magnitude higher to have good regulation. If the converter switching frequency (f_s) is selected on this basis, there is a possibility of insulation failure of HV transformer as it gets subjected to high voltage and high frequency together. Hence a suitable method of control is evolved to achieve the required objectives.

PM-SRC is chosen as the power-processing unit. From fig. (6), it can be observed that frequency of the rectified tank current pulses is double that of f_s. For good regulation, there should be at least one current pulse between two consecutive load pulses to replenish the charge taken during the load pulses. In other words, load switching frequency (f_L) and frequency of current pulses charging the output capacitor must be equal. This can be met if f_s is selected as half the f_L. As f_L is 125 kHz, f_s is taken as 62.5 kHz.

In this method of control, if load switching and converter switching are done independently, under practical circumstances, it is not possible to have f_s exactly half of f_L. If this relationship of switching frequencies is not maintained exactly, there can be unequal amounts of charge supplied to the output capacitor during any two consecutive intervals of load pulses. In addition, there will be two different frequencies injected in the output stage. It results in beat frequency oscillations in the output voltage waveform. These aspects adversely influence the output voltage regulation.

To overcome this problem, converter switching needs to be synchronized with the load switching. This completely eliminates the beat frequency oscillations and steady output voltage waveform is obtained. Also, excellent output voltage regulation is achieved. With this method of control, it is possible to operate the converter at moderate switching frequency. It helps in preventing the serious problem of insulation failure of HV transformer, which may otherwise exist at high frequencies. In addition, the device losses and transformer losses are also low providing high efficiency. The block diagram representing this proposed method of control is shown in the fig. (7).

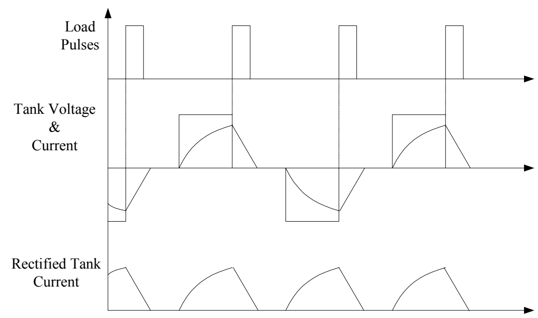


Fig. 6

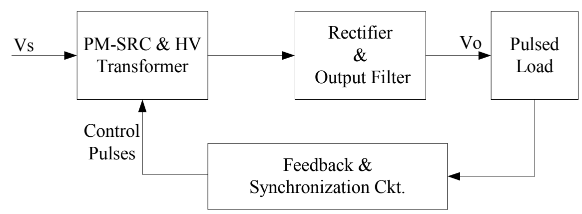


Fig. 7

IV. SIMULATION AND EXPERIMENTAL RESULTS

The converter is designed and built for the specifications mentioned earlier and its performance is observed through simulation as well as experiment. The converter is designed for a quality factor of 0.667 and $f_s / f_r = 1.05$. f_r is the resonant frequency of the tank circuit. Values of the components, like resonant inductor (L_r), resonant capacitor (C_r), transformer turns ratio (n), and output capacitance (C_o) are as follows.

$L_r = 173.21\ \mu H$, $C_r = 41.3$ nF, n = 2.07, $C_o = 12\ \mu F$.

Fig. 8 (a) to fig. 8 (f) present simulation waveforms and fig. 9 (a) to fig. 9 (h) present experimental waveforms. The tank voltage and current waveforms are shown for min., nominal and max. values of the supply voltage. Waveforms showing synchronous operation of the converter are presented. Output voltage waveforms showing pulsed loading, droop, and regulation are shown under nominal value of supply voltage. Control to output characteristic i.e., output voltage vs. duty cycle is shown. Transient response of the converter is presented under open loop condition for step change in control signal.

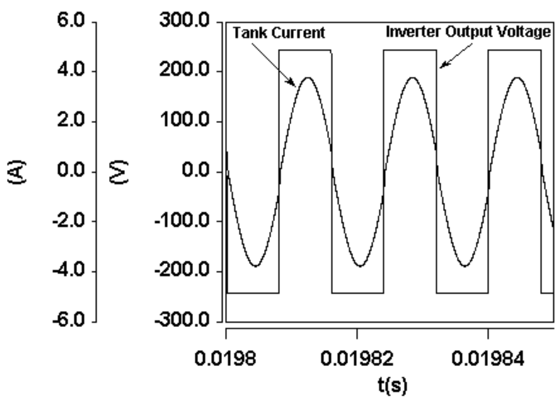


Fig. 8 (a) Tank voltage and current waveforms (Vs=243 V)

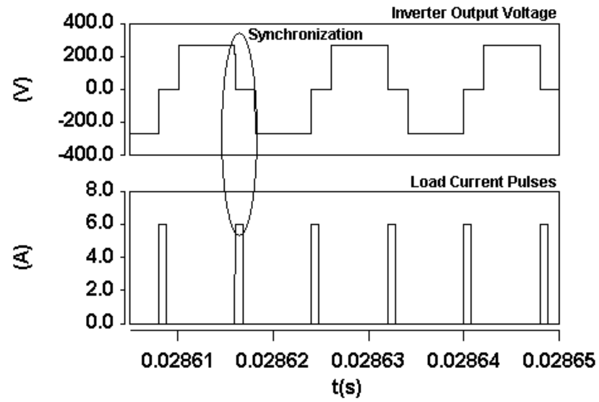


Fig. 8 (d) Synchronous operation of converter and load (Vs=270 V)

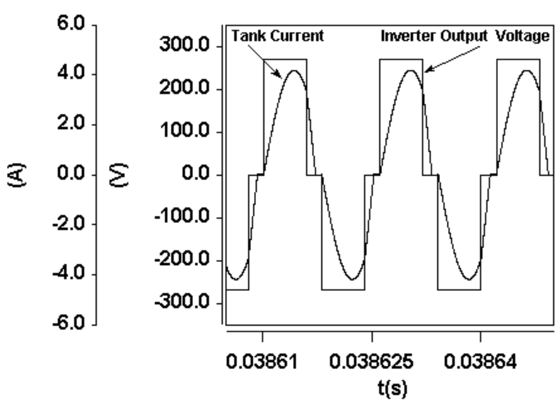


Fig. 8 (b) Tank voltage and current waveforms (Vs=270 V)

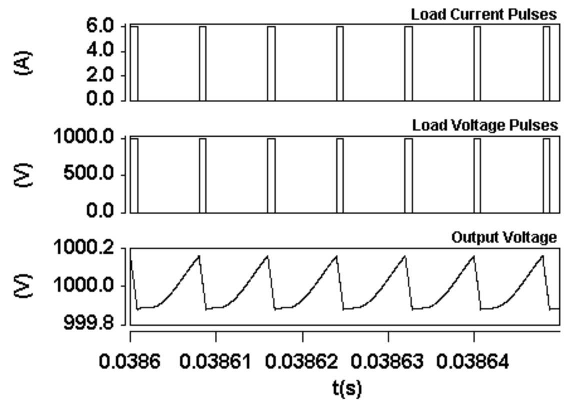


Fig. 8 (e) Output voltage, load voltage, and load current (Vs=270 V)

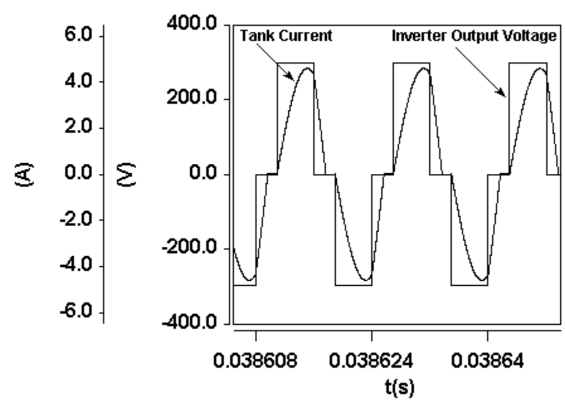


Fig. 8 (c) Tank voltage and current waveforms (Vs=297 V)

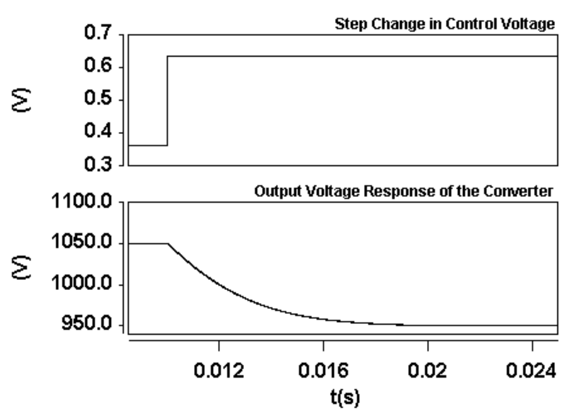


Fig. 8 (f) Step response of the power converter

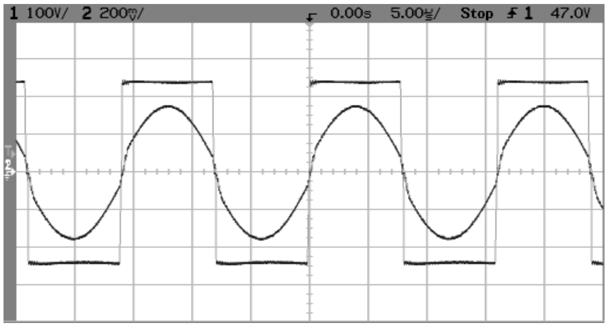


Fig. 9 (a) Tank voltage and current waveforms (Vs=243 V)
(Voltage: 100 V/div., Current: 2 A/div.)

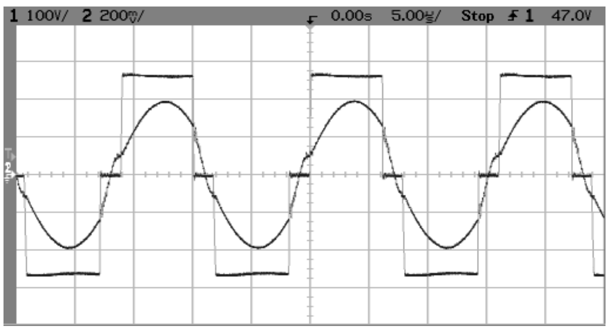


Fig. 9 (b) Tank voltage and current waveforms (Vs=270 V)
(Voltage: 100 V/div., Current: 2 A/div.)

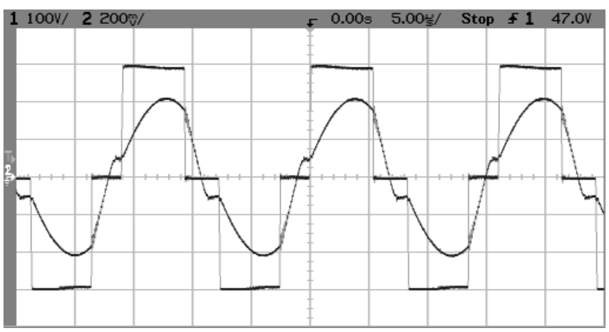


Fig. 9 (c) Tank voltage and current waveforms (Vs=297 V)
(Voltage: 100 V/div., Current: 2 A/div.)

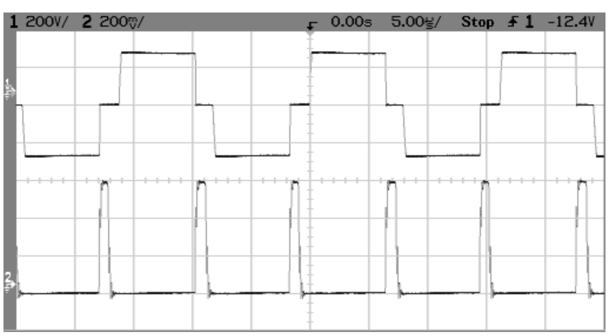


Fig. 9 (d) Synchronous operation of converter and load (Vs=270 V)
(Voltage: 200 V/div., Current: 2 A/div.)

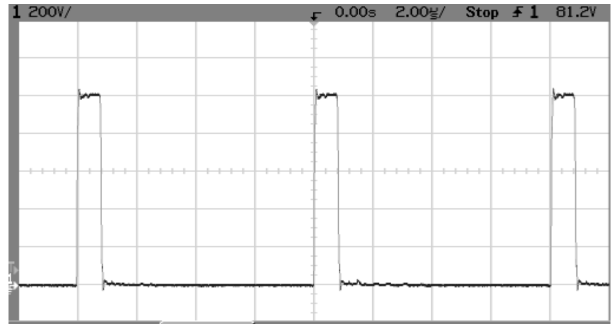


Fig. 9 (e) Load voltage waveform (Vs=270 V)
(Voltage: 200 V/div.)

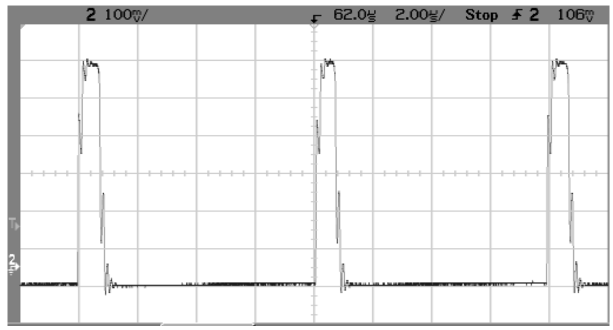


Fig. 9 (f) Load current waveform (Vs=270 V)
(Current: 1 A/div.)

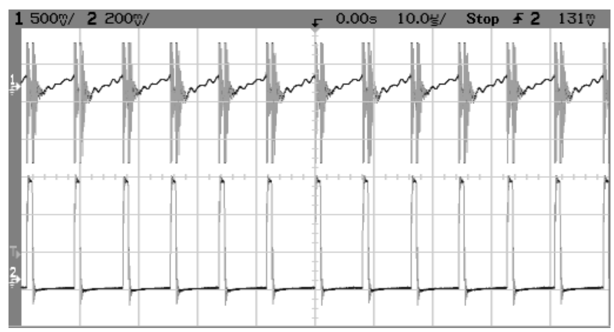


Fig. 9 (g) Output voltage and pulsed current waveform (Vs=270 V)
(Voltage: 500 mV/div., Current 2 A/div.)

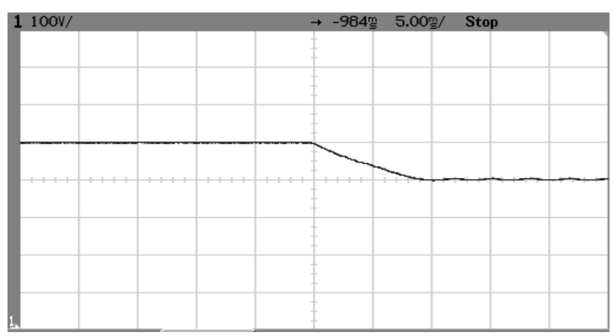


Fig. 9 (h) Transient response for step change in control signal
(Voltage: 100 V/div., Time: 5 msecs/div.) Response time = 10 msecs

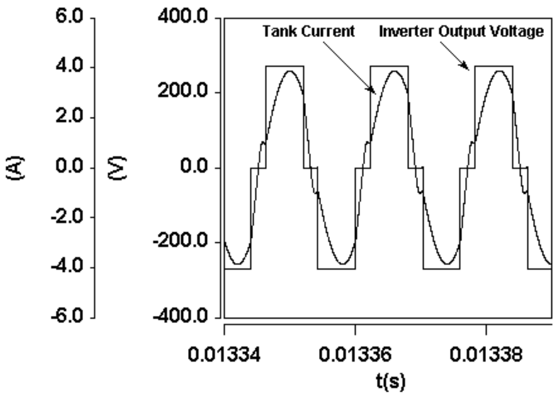


Fig.10 Tank waveforms with transformer parasitic elements (Vs=270 V)

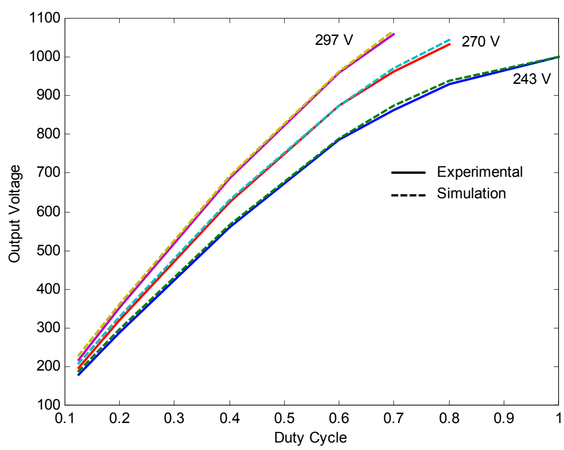


Fig. 11 Control to output characteristic

IV. DISCUSSION

From the simulation waveforms, it can be observed that under closed loop operation the converter should ideally operate in mode-1 at lower values of supply voltage and mode-3 at nominal and higher values of supply voltage. It is due to the reduction of duty cycle at higher supply voltages. The quality factor remains same under all conditions of supply voltage. But the experimental waveforms of tank voltage and current deviate from the ideal simulation waveforms at higher values of supply voltages. At these voltages, the converter operates in mode-2. The discrepancy is due to the effect of the parasitic winding capacitance of the HV transformer. This effect is confirmed again through simulation by addition of the parasitic winding capacitance to the transformer. It is shown in fig. 10. Under mode-2 operation, additional circuit is required to achieve zvs operation of the lagging leg switches of the inverter.

Control to output characteristic obtained through simulation and experiment match very closely. This characteristic is shown in fig. 11. It is for min., nominal, and max. values of the source voltage. The characteristic is not linear in the entire range of duty cycle. It may be approximated as linear for duty cycles in the range from 0 to 0.6. Output voltage response is more in this range of duty cycle than for the higher values.

Transient response of the power converter is studied through simulation as well as experiment. Output voltage response for step change in control signal exhibits first order characteristic. It has a response time of 10 milli-sec. First order characteristic of the converter makes the feedback design simple.

Due to the synchronous switching of the converter and pulse load, excellent regulation is obtained and output voltage waveform is steady without any beat frequency oscillations.

V. CONCLUSIONS

The proposed method of control for HV power supply is studied under various line and pulse load conditions. The regulation is found to be < 0.001 % and droop is less than 0.5V/micro-sec. As the converter is switched at half the pulse load frequency (a moderate switching frequency), transformer insulation is safe from failure. Due to synchronized switching of the converter with the load pulses, there is no problem of beat frequencies in the output voltage waveform. Though the load is of pulsed nature, its duty cycle and frequency being constant, it is equivalent to constant average load. As the converter can be considered being loaded at average value of its pulse load, zvs circuit need to be designed only for nominal value of the input voltage. As the variation of the input voltage is only a transient, its effect need not be considered for the design of the zvs circuit. The efficiency of the converter is greater than 94 % in the entire range of supply voltage variations.

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