Comparison of High Voltage DC Power Supply Topologies for Pulsed Load Applications

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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 the converter needs to be switched at much higher frequency than the pulse load frequency, transformer poses serious problems of insulation failure and higher losses. Two power converter topologies are presented, one with input voltage modulation (IVM) and the other with output voltage modulation (OVM). In each of the topologies, power conversion is done in two stages to take care of the critical aspects of the HV transformer and to satisfy all the performance specifications. Both the topologies are critically evaluated for their performance and their relative merits and demerits are discussed.**

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]. 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 [4].

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.

This paper presents two power converter topologies for high-voltage DC power supplies subjected to pulse loads with stringent performance specifications demanding tight output voltage regulation and high efficiency. Radar power supplies are subjected to pulse 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 should switch at-least at twice the 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.

Above-mentioned drawbacks led to the development of two-stage power conversion. In each of the proposed topologies, two power converters are used, namely, base power supply (BPS) and fast power supply (FPS). BPS handles large power, large output voltage, and switches at low frequency. FPS handles small power, small output voltage and switches at high frequency. In one of the topologies, FPS modulates the input voltage of BPS, which is named as IVM power converter. In the other topology, FPS modulates the final output voltage, which is named as OVM power converter. This two-stage power conversion helps in overcoming the problems of HV & HF transformer, provides fast response and good regulation without compromising the efficiency constraint.

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

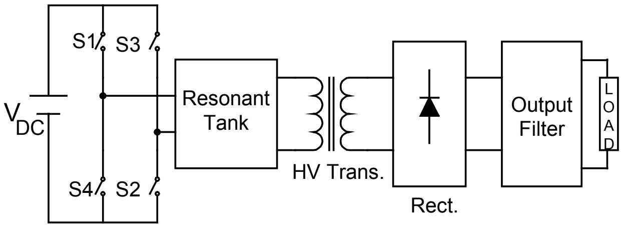


Fig. 1

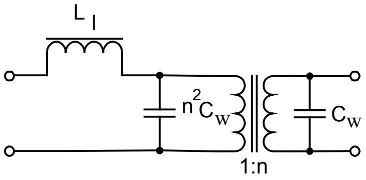


Fig. 2

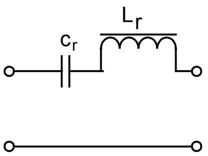


Fig. 3 (a)

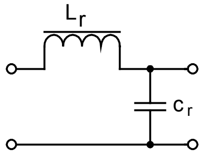


Fig. 3 (b)

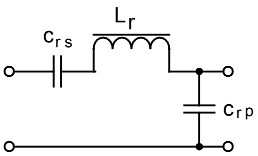


Fig. 3 (c)

TABLE I

Supply Voltage: 270 VDC ± 10 %

Output Voltage: 1KV

Peak Power: 6 KW

Average Power: 600 W

Regulation: < 0.01 %

Droop: 0.5V/ μ sec.

Load Switching Freq.: 125 K HZ

Efficiency: > 85 %

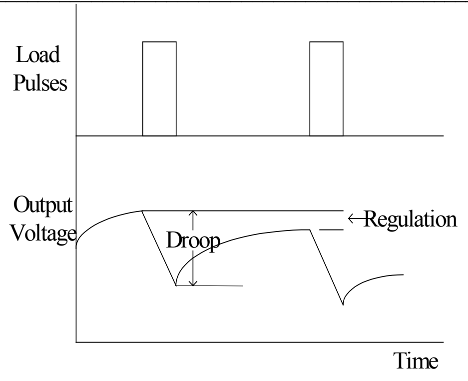
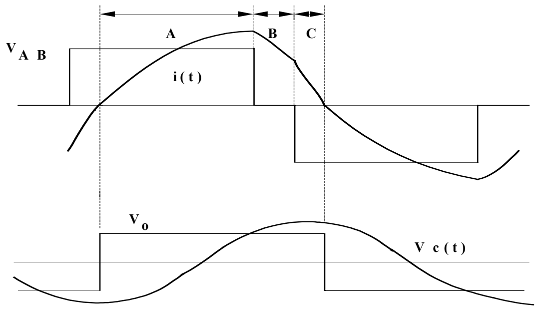


Fig. 4

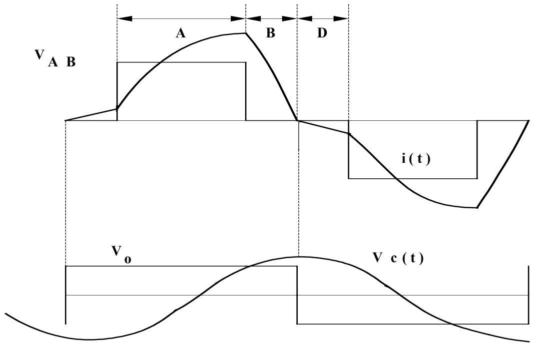
output voltage, v_{AB}, resonant capacitor voltage, $v_c(t)$, and output voltage, V_o, under the three modes are shown in fig.5. The various sub-periods are shown as A, B, C, D, and E. The general equations describing the LC tank circuit with excitation $(V_{in} - V_{out})$ are given by

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

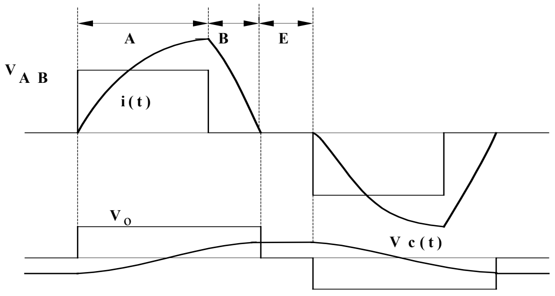
$$\begin{aligned} v_c(t) = &- [(V_{in} - V_{out}) - V_c(0)]\cos\omega_r t + Z_c I(0)\sin\omega_r t \\ &+ (V_{in} - V_{out}) \end{aligned} \tag{2}$$



(a) Mode-1 operation



(b) Mode- 2 operation



(c) Mode -3 operation

Fig. 5. Waveforms of PM-SRC

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 POWER CONVERTER TOPOLOGIES

The block diagrams of the proposed topologies i.e., IVM and OVM power converters for the pulsed load application are shown in figs.6 and 7 respectively. Each of the topologies consists of two PM-SRCs namely Base Power Supply (BPS), which is an uncontrolled converter & the other, Fast Power Supply (FPS) which is a controlled converter. In the IVM converter, the input voltage to the BPS is provided as the sum of primary DC supply voltage and output of the FPS. Controlling the input of BPS through FPS regulates the final output voltage. BPS handles whole of the power and operates in mode-1 whereas power handled by FPS and its mode of operation depend on supply voltage. In the OVM converter, the output voltages of the BPS and FPS are added and regulation is achieved through FPS. Here BPS handles majority of the power and operates in mode-1 whereas power handled and mode of operation of FPS again depend on the supply voltage.

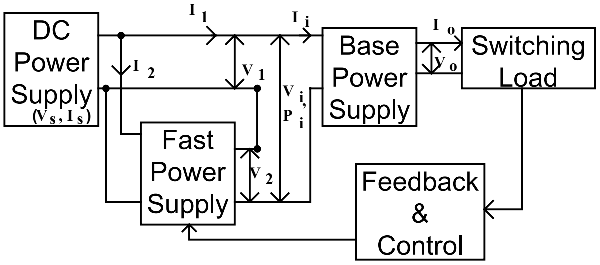


Fig. 6. IVM Power Converter

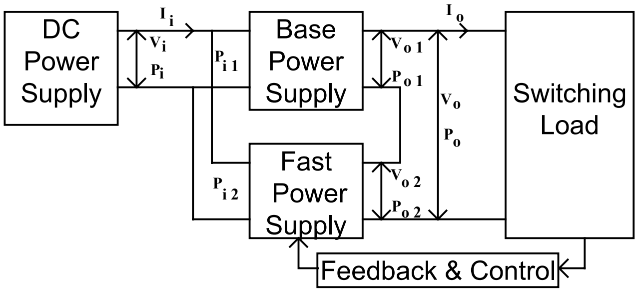


Fig. 7. OVM Power Converter

$f_B = \frac{n_1}{2} \times f_L$, and $f_F = n_2 \times f_L$

f_B, f_F, and f_L are switching frequencies of BPS, FPS and load respectively. n_1 and n_2 are integers. BPS is switched at a frequency such that frequency of its rectified tank current is an integral multiple of the load-switching frequency. FPS is switched at higher frequencies to the extent possible with n_2 as an integer. The values of f_B, and f_L are 62.5 kHz, and 125 kHz respectively for both the converters. The value of f_F is 625 kHz for IVM converter and 250 kHz for OVM converter. This type of frequency selection avoids the beat frequency oscillation in the final output voltage and provides fast response. The HV transformer insulation is subjected to a frequency of 62.5 kHz, which is within the safe limits. The ratio of switching frequency to the resonant frequency of tank ckt. is taken as 1.05 for BPS and FPS of both topologies.

IV. COMPARISON OF THE PROPOSED TOPOLOGIES

A relative comparison of the proposed topologies is done based on the following aspects.

A. Voltage and Power Division

In both IVM and OVM converters, BPS and FPS produce certain amount of voltage and handle certain amount of power based on the supply voltage variations. In these topologies, BPS is an uncontrolled converter and it is designed for total power and output voltage rating as per the specifications. The power rating and percentage output voltage rating of FPS are equal in magnitude for these topologies. For a variation of X% in the supply voltage,

$$\text{Max. \% of voltage to be produced by FPS} = \frac{2X}{(1+X)} \times 100$$

$$\text{Max. \% of power to be handled by the FPS} = \frac{2X}{(1+X)} \times 100$$

These percentages of voltage and power for FPS have to be calculated with respect to the input voltage and power rating of BPS for IVM converter. For OVM converter, these percentages are with respect to the final output voltage and power. For a 10% variation in the supply voltage, FPS output voltage and power ratings are 18.18%. In case of IVM converter, magnitude of FPS output voltage will be of the order of few tens of volts and for OVM converter it will be of the order of few KV. Hence FPS can be switched at much higher frequencies for IVM converter than for the OVM converter.

B. Efficiency

Overall efficiency expression for IVM and OVM converters are given as follows.

For η_1, η_2, and η as the BPS, FPS and overall efficiencies

$$\text{Overall efficiency } (\eta) = \frac{\eta_1 \eta_2 (1+K)}{(\eta_2 + K)} \quad \text{for IVM converter}$$

$$\text{Overall efficiency } (\eta) = \frac{\eta_1 \eta_2 (1+K)}{(\eta_2 + K\eta_1)} \quad \text{for OVM converter}$$

where $K = \frac{V_2}{V_1}$ for IVM, and $K = \frac{V_{o2}}{V_{o1}}$ for OVM converter.

Table II gives the individual efficiencies of BPS and FPS as well as overall efficiencies of the IVM and OVM converters for varying supply voltage. In both the topologies BPS is found to have very high efficiency. It is around 95% over the entire range of supply variations. Efficiency of FPS varies considerably over the full supply range. This is due to the variations in the output power developed by it. Overall efficiency of these topologies is much higher than 85%. It is dominated by the efficiency of BPS as it handles much higher power than FPS.

TABLE II

Supply Voltage (V)	IVM Converter η_1	η_2	η	OVM Converter η_1	η_2	η
243	95.2	82.1	91.57	95.02	84.45	92.33
270	95.2	76.4	92.59	95.47	78.22	93.5
297	95.2	5.1	89.13	95.76	4.92	92.03

C. Component Values and Tank Stresses

The prototypes made are as per the design specifications of table I. The design of BPS and FPS is carried out as explained in [7], and [8]. The component values like resonant inductor (L_r), resonant capacitor (C_r), transformer turns ratio (n), output capacitance (C_o) and switching frequency (f_s)

obtained for BPS and FPS of these converters are in table III. For a 10% variation in supply voltage, BPS and FPS are designed for 600 W and 109 W respectively.

TABLE III

Parameters	IVM Converter		OVM Converter	
	BPS	FPS	BPS	FPS
L_r (μH)	260.08	93.55	260.08	233.38
C_r (nF)	27.50	0.76	27.50	1.91
n	1.69	0.23	1.69	0.38
C_O (μF)	12.0	5.8	12.3	12.3
f_S (KHz)	62.50	625.0	62.5	250.0

It can be observed that BPS has same component values for both IVM and OVM converters whereas for FPS they are different. It is due to the differences in their switching frequencies and output voltage magnitudes. Peak tank stresses i.e., peak tank current (Ip) and peak resonant capacitor voltage (Vcp) for BPS and FPS of the two topologies for nominal supply voltage are shown in table IV.

TABLE IV

Parameters	IVM Converter		OVM Converter	
	BPS	FPS	BPS	FPS
Ip (A)	3.079	0.976	3.087	0.956
Vcp (V)	296.33	245.41	297.11	243.25

These tank stresses are close to 1p.u. corresponding to their base values calculated as $I_B = V_S / Z_c$ and $V_B = V_S$. Where I_B, V_B, V_S, and Z_C are base current, base voltage, supply voltage and characteristic impedance of the resonant tank respectively.

D. Quality Factor and Modes of Operation

Mode of operation of a PM-SRC is a function of duty cycle and quality factor (ζ) of the tank ckt. Quality factor is in turn dependent on the amount of loading on the converter with other parameters being constant. In case of pulsed load, though it is of pulsed nature, duty cycle and frequency of the load are fixed. Hence it can be considered as an equivalent constant average load. In each of the proposed topologies, BPS and FPS are present. Under varying conditions of supply voltage, effective loading changes only for FPS in IVM and for both BPS and FPS in OVM converter. This results in variation of their quality factors.

In the IVM converter, under supply voltage variations, input voltage of BPS is controlled to be constant by FPS. Final output voltage across the load is produced by BPS only. Hence equivalent load on BPS is always constant which makes its quality factor to remain constant. Mode of operation for BPS doesn't change as its duty cycle and quality factor are fixed. The output voltage of FPS is variable based on the supply voltage variations. Its output current or load current is same as the input current of BPS, which is constant. As the output voltage of FPS varies, effective load on FPS changes. For an increasing value of supply voltage, output voltage of FPS decreases and its effective loading increases. Increase in load results in increase in its quality factor and vice-versa. Mode of operation for FPS changes as its duty cycle and quality factor are variable.

In OVM converter, final output voltage is sum of the outputs of BPS and FPS. For variations in the supply voltage, output voltage of BPS changes due to its uncontrolled nature. To regulate the final output voltage to be constant, FPS has to change its output voltage. Hence there are changes in the output voltages of BPS as well as FPS for this topology. This results in variation in the loading for both BPS and FPS and their quality factors. Mode of operation for BPS doesn't change as its duty cycle is fixed and close to unity. For FPS there are changes in the duty cycle as well as quality factor, which make it to change its mode of operation under supply variations.

Table V gives the quality factors and modes of operations for BPS and FPS of both the topologies for minimum, nominal and maximum values of the supply voltage.

TABLE V

Supply Voltage	IVM Converter				OVM Converter			
	BPS		FPS		BPS		FPS	
(V)	ζ	Mode	ζ	Mode	ζ	Mode	ζ	Mode
243	0.667	1	0.678	1	0.825	1	0.677	1
270	0.667	1	1.332	2	0.74	1	1.360	2
297	0.667	1	37.30	2	0.677	1	66.17	2

FPS operates in mode-1 and mode-2 for IVM as well as for OVM converters. At 297 V, ζ of FPS for OVM is larger than for IVM. It is due to small difference in the output voltages of FPS of IVM & OVM converters at this input voltage. For mode-2 operation, there is a need for additional circuitry for achieving zvs for the lagging leg switches of the converter.

E. Effect of Winding Capacitance

Due to large number of secondary turns of the HV transformer, the parasitic winding capacitance becomes considerable in magnitude. This gets multiplied by square of the turns ratio when reflected to the primary winding. Operation of the PM-SRC gets effected if the reflected winding capacitance becomes comparable with the resonant capacitor of the tank ckt. Winding capacitance results in increase in gain of the converter, increase in tank stresses, change in the tank current waveform, delays and current spikes.

In both of the topologies, BPS produces output voltage in tens of kV based on the output voltage rating. Hence, its reflected winding capacitance can be considerable and may interfere with the operation of the converter. The effect of it on mode-1 operation is shown in the form of waveforms in fig. 8(g). FPS of IVM converter produces only few tens of volts. So winding capacitance need not be considered. FPS of OVM converter produces few kV. So there is a need to consider this effect for FPS of this topology. Winding capacitance effect is shown for mode-2 and mode-3 operations in figs. 8 (h) and (i) respectively. Cw′ is the ratio of reflected winding capacitance to resonant capacitor of the tank circuit.

F. Transient Response

Transient response of these power converters is observed for small perturbations in the supply voltage as well as in the control signal. BPS is an uncontrolled converter and is relatively much slower than FPS due to lower switching frequency and larger reactive elements. For small perturbations in the supply voltage, output voltage response for both the topologies is seen to be mainly dictated by BPS and have almost equal response time. In IVM converter, for control signal perturbations, output voltage response is still dictated by BPS as the change has to go through it. For OVM converter, though individual outputs are added to produce the final output voltage, control exercised through FPS leads to variations in the loading of both BPS and FPS. This again makes the output response dependent on BPS. For both IVM and OVM, it is 4 msecs.

G. Beat Frequency Oscillations

As the converters are pulse loaded, the output stages of these topologies may be subjected to more than one frequency. This may result in beat frequency oscillations in the output voltage if proper care is not taken. For IVM converter, effect of FPS frequency component on the final output stage is negligible. As BPS is switched at 62.5 kHz, its rectified tank current has a frequency of 125 kHz. Hence the output stage is subjected to only one frequency component. Under synchronized operation of the converter and load, there are no beat frequency oscillations. For OVM converter, the output stage is subjected to frequency components due to BPS, FPS and load. But the frequency selection of BPS and FPS are done in such a way that synchronized operation will not result in any beat frequency oscillations in the output voltage.

V. RESULTS

The waveforms of the two topologies are shown in figs. 8 (a) to (i). These are for a nominal input voltage of 270 V. Fig. 8(a) to (c) give the IVM converter tank waveforms for BPS, FPS and load waveforms respectively. Figs. 8(d) to (f) give the OVM tank waveforms for BPS, FPS and load waveforms. Fig. 8(g) to (i) give the waveforms for effect of winding capacitance.

V. CONCLUSIONS

Comparative study has been done for the proposed topologies. In each of the topologies, power handling is done by both BPS and FPS. BPS, an uncontrolled converter, has the capability of handling total power in IVM and OVM topologies. Whereas FPS handles only certain percentage of the total power based on the supply condition and regulates the output voltage. BPS always operates in square wave mode (mode-1), hence zvs is ensured under all conditions of supply and load. For FPS, provision is made for ensuring zvs under varying conditions of supply voltage as it operates in mode-2 also. The design criteria are same for both IVM and OVM converters. As far as BPS is concerned, it has same component values in both IVM and OVM converters. The component values for FPS differ in these topologies due to the difference in magnitudes of the voltages produced and difference in the switching frequencies. In case of OVM converter, voltage doubler is used at the output stage of FPS but not with FPS of IVM converter. Both topologies have first order response and have simple feedback loop design.

The difference in these topologies lies in the way they regulate the output voltage. IVM converter regulates its output voltage by controlling input voltage of its BPS. Whereas, OVM converter regulates its output voltage by adding output of its FPS to that of its BPS. Due to this, there is difference in the magnitudes of the voltages produced by FPS and the selected values of the switching frequencies in the two topologies. For IVM converter, higher switching frequency could be selected for FPS as its output voltage is not more than few tens of volts whereas for FPS of OVM converter it is few kV. For OVM converter, there is a possibility of insulation failure of the FPS transformer if higher switching frequencies are selected. Transient response is found to be same for both the topologies for supply voltage perturbations as well as control signal perturbations. Beat frequency oscillations in the output voltage can be avoided if the converter and load switchings are synchronized. At nominal supply voltage, overall efficiency of both the topologies is found be more than 92%. Finally, both the topologies satisfy all the performance requirements and take care of critical aspects of the HV transformer.

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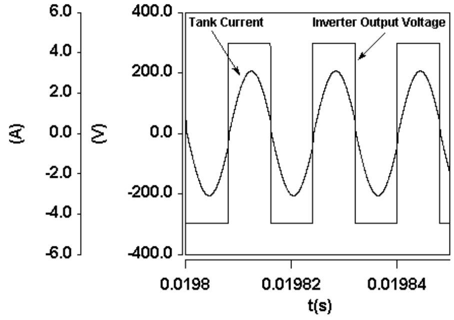

Fig. 8(a) BPS tank Waveforms (IVM)

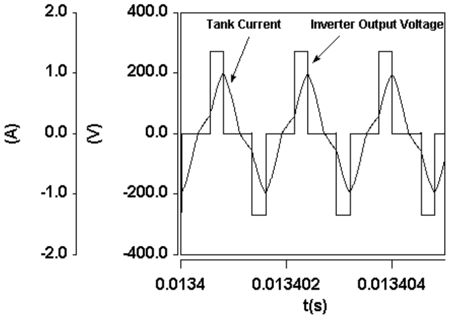

Fig. 8(b) FPS tank Waveforms (IVM)

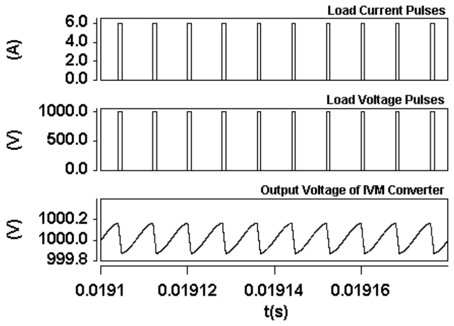

Fig. 8(c) Load Waveforms (IVM)

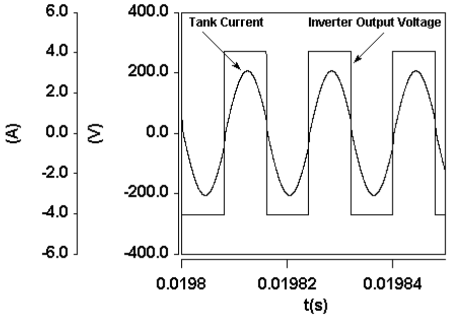

Fig. 8(d) BPS tank Waveforms (OVM)

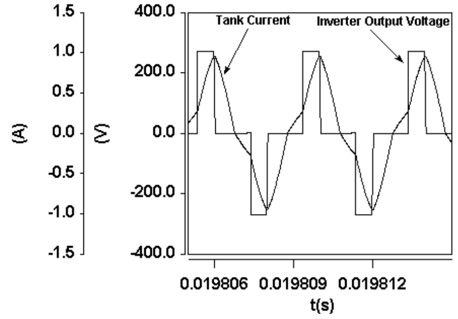

Fig. 8(e) FPS tank Waveforms (OVM)

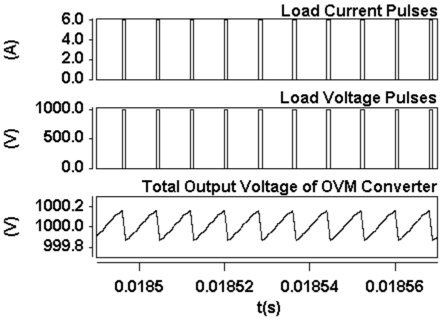

Fig. 8(f) Load Waveforms (OVM)

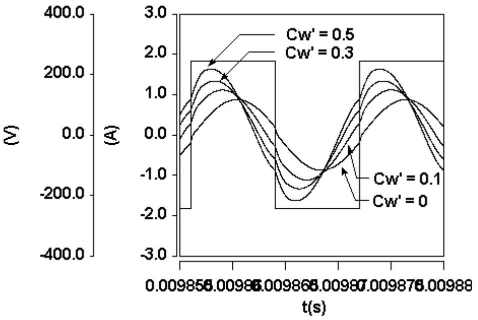

Fig. 8(g) Winding capacitance effect on mode-1 operation

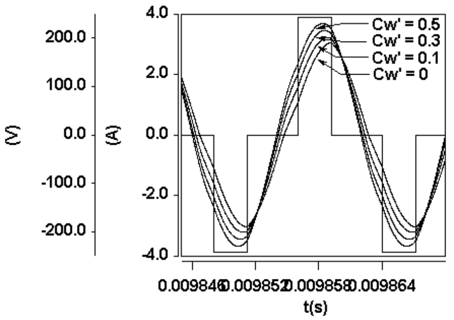

Fig. 8(h) Winding capacitance effect on mode-2 operation

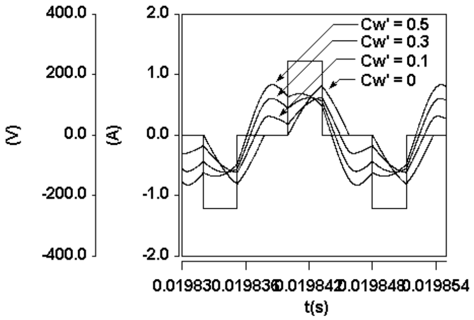

Fig. 8 (i) Winding capacitance effect on mode-3 operation