STUDY AND COMPARISON OF REACTIVE POWER COMPENSATION SCHEMES FOR AIR-CORE TRANSFORMER IN ELV-TYPE DC ACCELERATORS

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Abstract

The ELV-type accelerators use air-core, multi-secondary step-up transformer to generate the high voltage. The transformer has large leakage inductance and small magnetizing inductance. Suitable compensation scheme is required to minimize the reactive power loading on the source feeding the primary winding. The results of studies done to investigate suitability of various compensation networks are presented in this paper. Characteristics are studied and compared using simulation software PSpice, wherein normalized results suitable for comparison are directly obtained.

INTRODUCTION

The high-power ELV-type electron accelerators are widely used in industrial and research applications. The scheme for generating high voltage in these machines is based on air-core, multi-secondary step-up transformer. Each secondary has voltage doubler rectifier and filter, the outputs of which are connected in series to generate the high voltage. As opposed to the conventional transformer, the air-core transformer has large leakage inductance (L_s) and small magnetizing inductance (L_m). Moreover, the values of L_s and L_m are nearly the same [1]. A simplified equivalent circuit is shown in figure 1. The air-core transformer has poor regulation and draws a large reactive power from the source feeding the primary winding. Suitable compensation scheme must therefore be employed to minimize these undesirable effects. The compensation network (CN) should offer following benefits: (1) Near-unity power factor operation under all loading conditions. (2) Nearly load independent output voltage. (3) Minimum additional reactive components. (4) If possible, no additional compensating inductor.

The conventional compensation scheme [1] however can either achieve good voltage regulation or minimum reactive power depending on the operating frequency. Besides, the network uses an additional bulky inductor.

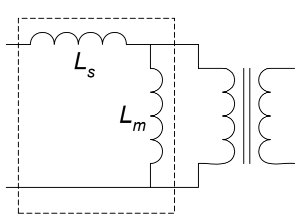

Figure 1: Simplified equivalent circuit of air-co re transformer in ELV-type accelerators.

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Therefore, the possibility of using various other CNs is examined. In this paper, the results of studies done to investigate suitability of various CNs are presented. Characteristics of the CNs are studied and compared using PSpice [2].

COMPENSATION NETWORKS

The CNs considered for study and comparison are shown in Fig. 2. In the networks N1, N2 and N3, the inductive components of air-core transformer are compensated using one or more capacitors. The network N4 uses additional inductor (L_a) and is the conventional CN [1]. PSpice is used for analysis of these CNs. However, a method described in [3] is followed to obtain the normalized results for comparison directly from the simulation. Amplitude of input source V_{in} is assumed to be unity. The values of L_s and L_m are assumed to be the same [1]. Resonant frequency (f_o), characteristic impedance (Z_n) and circuit Q are defined as:

$$f_o = \frac{1}{2\pi\sqrt{(L_s + L_m)C}}, Z_n = \sqrt{\frac{(L_s + L_m)}{C}}, Q = \frac{R_{ac}}{Z_n} \quad (1)$$

where C is the compensating capacitor and R_{ac} is the resistive equivalent of secondary-side doubler-rectifier and load reflected on the primary side. Table 1 give the values of L_s, L_m and C making f_o and Z_n unity.

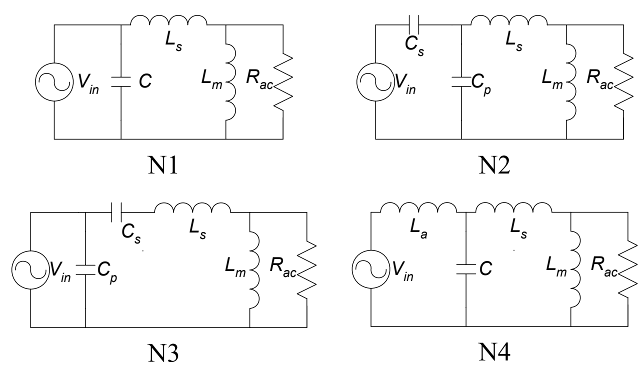

Figure 2: Compensation networks.

Table 1: Values of L_s, L_m and C used in simulation.

Component	Compensation Network			
	N1	N2	N3	N4
$L_s = L_m$	$\frac{(1/2\pi)}{2}$			
C	$(1/2\pi)$	—	—	$(1/2\pi)$
$C_s = C_p$	—	$(1/2\pi) = C$	$2(1/2\pi) = 2C$	—

SIMULATION RESULTS

The CNs shown in Fig. 2 are simulated using PSpice to visualize their characteristics sweeping the operating frequency. With circuit parameters described in previous section, normalized results are directly obtained from the simulation. X-axis of the plots is operating frequency normalized to the resonant frequency. Circuit voltages and currents (displayed on Y-axis) are normalized with reference to V_{in} and $\left(V_{in}/Z_n\right)$, respectively.

Compensation Network N1

The transformer and load is compensated by a capacitor *C*. Figure 3 shows the plots of load voltage (voltage across R_{ac}) and source current amplitude and its phase for different values of *Q*. Following observations are made at the resonant frequency:

1. The load voltage is a function of Q but remains nearly constant only for higher values of Q. The maximum voltage gain is 0.5.
2. The source current reduces as Q increases ensuring good part-load efficiency.
3. The phase angle between the source voltage and current (φ) depends on Q. They are nearly in-phase only for higher values of Q but φ changes steeply with slight shift in operating frequency.

Compensation Network N2

Two compensating capacitors C_s and C_p are used. Under the assumption that L_s and L_m are equal, if C_s and C_p are also chosen to be of the same value then load voltage becomes completely independent of *Q* at resonant frequency as shown by the plots of Fig. 4. Following observations are made at the resonant frequency:

1. The output voltage is independent of Q with voltage gain of 0.5.
2. The source current reduces as Q increases ensuring good part-load efficiency.
3. φ is zero, independent of Q.

Compensation Network N3

The network N2 has all desirable features required for a CN listed previously. However, the voltage gain is only 0.5 (see Fig. 4) necessitating a high-voltage input source.

In network N3, C_s and C_p are located in such a way that C_s compensates L_s and series combination of C_s and C_p compensates (L_s+L_m). The characteristics of N3 are plotted in Fig. 5. Similar to network N2, load-independent output voltage, in-phase source voltage and current waveforms and good part-load efficiency is observed for network N3 at resonant frequency. Moreover, the voltage gain of N3 is unity at resonant frequency.

Compensation Network N4

The network N4 with capacitor *C* and inductor L_a has been conventionally used for the compensation [1]. Figure 6 shows its typical characteristics for L_a = (L_s+L_m). At operating point f_1, output voltage is independent of *Q*

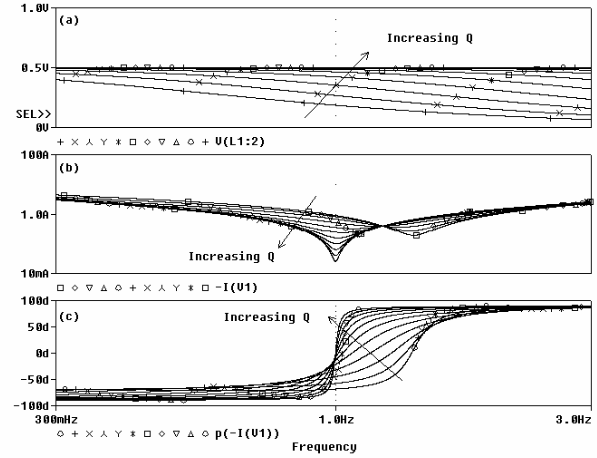

Figure 3: Characteristics of N1. (a) Load voltage, (b) source current amplitude and (c) source current phase.

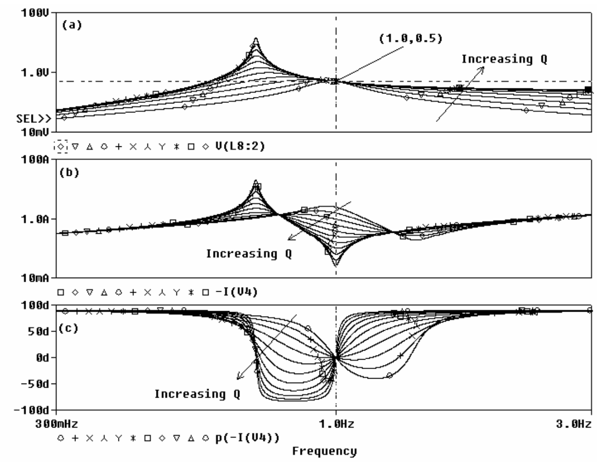

Figure 4: Characteristics of N2. (a) Load voltage, (b) source current amplitude and (c) source current phase.

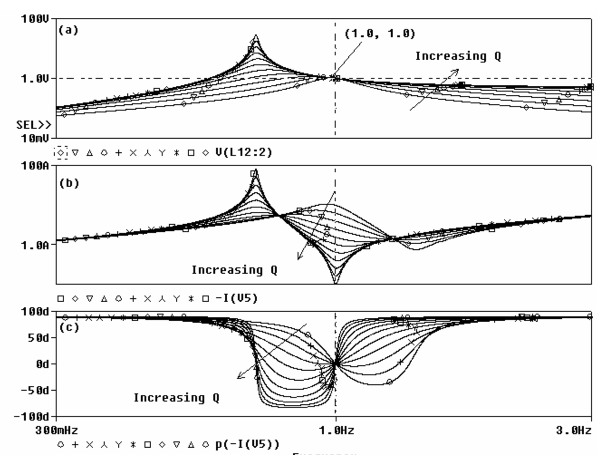

Figure 5: Characteristics of N3. (a) Load voltage, (b) source current amplitude and (c) source current phase.

resulting in good voltage regulation but non-zero *φ*. At operating point f_2, *φ* is zero and independent of *Q* resulting in minimum reactive power loading but poor voltage regulation.

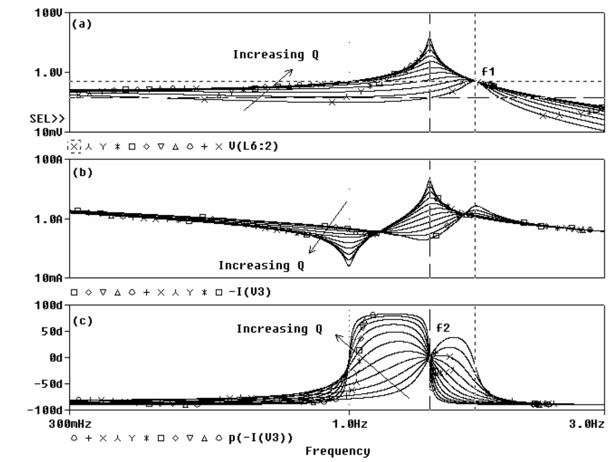

Figure 6: Characteristics of N4. (a) Load voltage, (b) source current amplitude and (c) source current phase.

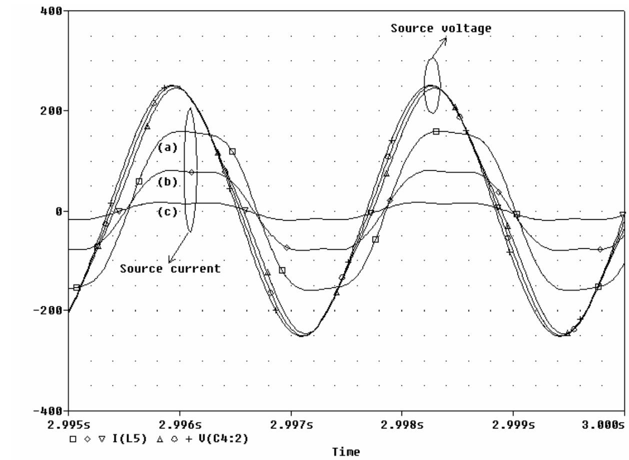

Figure 7: Source voltage and current waveforms of an air-core transformer compensated by network N3.

COMPARISON AND DISCUSSION

Based on the simulation results described in the previous section, following comparative observations can be made:

1. Network N1 neither provides constant output voltage nor in-phase source voltage and current under all loading conditions. Therefore, this CN is not advantageous for the present application.
2. Network N4 offers constant output voltage as well as in-phase source voltage and current under all loading conditions but at different operating frequencies. Therefore, depending on operating point either good voltage regulation or minimum reactive power can be achieved. Besides, the network uses an additional bulky inductor for compensation.
3. Adding another capacitor in network N1 at appropriate location results into the networks N2 and N3 which offer all desirable characteristics. These networks offer load-independent output voltage as well as the in-phase source voltage and currents simultaneously at one operating points. The only limitation of network N2 (that is, voltage gain of 0.5 at resonant frequency) is overcome in network N3. Therefore networks N2 and N3 can be advantageously used for the compensation.
4. Although the total value of capacitances in N3 is 4 times of that in N2, the capacitor voltage is also half. The stored energy and therefore approximately the total volume of capacitors in both the networks is the same.
5. While network N4 has been conventionally used with square-wave input source voltage, sinewave input sources need to be used with networks N2 and N3. Also the inherent protection of input source against the load short circuit offered by network N4 is absent in N2 and N3.

To confirm the observations made in the previous section, a air-core transformer with 31:2880 step-up turns ratio and having L_s=L_m=0.2 mH is simulated with different CNs studied. On the secondary side, the transformer has voltage doubler rectifier with 260 nF filter capacitors. The rectifier is loaded with 0.52 A (full-load) dc current source. The sine-wave input source is modeled as an ideal source of 250 V peak / 430 Hz in series with 75 μH inductance. Illustratively, the simulated waveforms for the source voltage and current waveforms are shown in Fig. 7 for network N3 with C_s=C_p=685 μF. Source current waveforms (a), (b) and (c) correspond to 100%, 50% and 10% loading condition, respectively. The non-sinusoidal source current and the slight phase lag is due to nonlinear load on the transformer secondary (instead of the resistive load approximated in the earlier results). More importantly, it is interesting to notice that the phase between source voltage and current does not change with the load. The output dc voltage is observed to increase only by 5 % from full-load (38 kV) to no-load.

CONCLUSION

Simulation results of different CNs required with air-core transformer in ELV-type accelerators are presented in this paper. As opposed to the network used conventionally (N4), two CNs (N2 and N3) are shown to offer load independent output voltage as well as unity power factor operation. These networks, being composed of only capacitors, are compact, light-weight and less noisy.

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