CHAPTER 6

STEADY STATE ANALYSIS AND SIMULATION OF THE IPM GENERATOR FEEDING A RECTIFIER-BOOST-RESISTIVE LOAD

6.1 Introduction

In this chapter, the steady state analysis and simulation of the IPM generator feeding a rectifier-boost- resistive load will be performed. A boost converter is normally used when the needs of the load are such that a load voltage higher than the supply voltage anp-1vequire A
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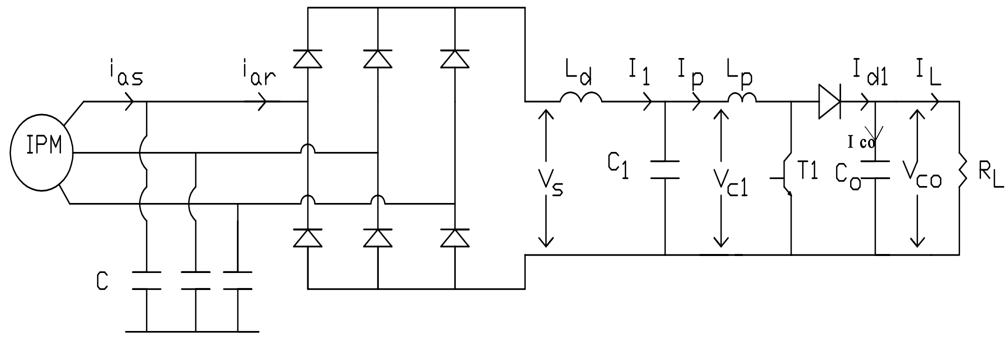


Figure 6.2. Schematic diagram of an IPM generator feeding a rectifier-boost-resistive load

Figure 6.3. Schematic diagram oa boost converter in mode 1 operation

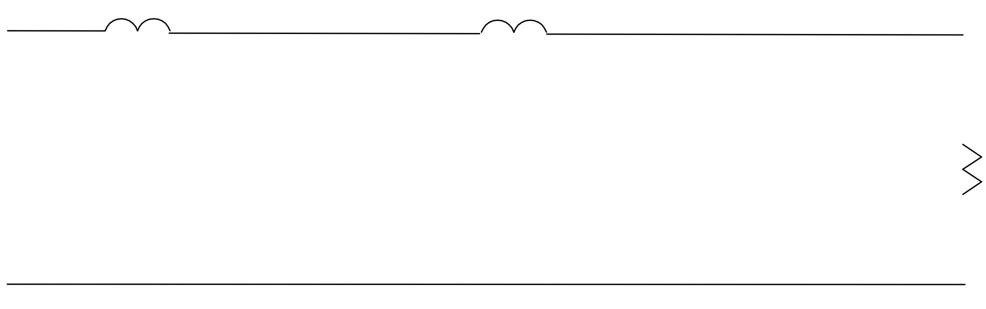


Figure 6.4. Schematic diagram of a boost converter operating in modes 2 and 3

Mode 1:S_1 T1 ON $0 \le t \le d_1T$

The schematic diagram of mode 1 is shown in Figure 6.3. The systems equations can be written as

$$L\frac{dI}{dt} = V - V_1$$

$$C\frac{dV_1}{dt} = I - I$$

$$L\frac{dI}{dt} = V_1 - V_{co}$$

$$C_o\frac{dV_{co}}{dt} = -\frac{V_{co}}{R_L}$$

$$V_{co} = R_L I_L \; .$$

Mode 2: S_2 T1 OFF (I_p >0) $d_1T \le t \le d_2T$

For mode 2, shown in Figure 6.4, the systems equations can be written as

Mode 3: S_3 T1 OFF (Ip =0) ($d_1 + d_2$) T ≤ t ≤ ($d_1 + d_2 + d_3$) T

For mode 3, shown in Figure 6.4 with the understanding that the current in the inductor $L_p = 0$, the systems equations can be written as

$$
\begin{aligned}
L_d \frac{dI_1}{dt} &= V_s - V_c1 \\
C_1 \frac{dV_c1}{dt} &= I_1 \\
L_p \frac{dI_l}{dt} &= 0 \\
C_o \frac{dV_{co}}{dt} &= -\frac{V_{co}}{R_L} \\
V_{co} &= R_L I_L \;.
\end{aligned}
\qquad (6.3)
$$

The objective is to establish global equations for the system containing modes 1 and 2 and 3. Recognizing that the sum of the switching functions is

then S3 may be written as

The global state equations for the boost converter can be written as

$$L_d \frac{dI_1}{dt} = V_s - V_c1$$
$$C_1 \frac{dV_c1}{dt} = I_1 - I_p + S_3 I_p$$
$$L_p \frac{dI_l}{dt} = V_c1(1 - S_3) - V_{co}(1 - S_1 - S_3) \qquad (6.6)$$
$$C_o \frac{dV_{co}}{dt} = I_p(1 - S_1 - S_3) - \frac{V_{co}}{R_L} \ .$$

Following the same procedure as outlined in Chapter 5, if the state equations are perturbed and separated into their dc, ac, and higher order terms, at steady state the rate of change of the states for the dc component is zero, so the left side of the equations becomes zero. Thus, the dc components of the equations can be reduced to

$$V_s = V_c1$$
$$I_1 = I_p - s_3 I_p$$
$$V_c1 = \frac{(1 - s_1 - s_3)V_{co}}{1 - s_3} \qquad (6.7)$$
$$\frac{V_{co}}{R_L} = (1 - s_1 - s_3) I_p$$
$$V_{co} = R_L I_L \ ,$$

where the average values of the switching functions (i.e. s_1, s_2, and s_3) are their respective areas divided by the total time T. Thus, *003-T3 -222 d5720031*

$$s_1 = \frac{d_1 T}{T} = d_1$$
$$s_2 = \frac{d_2 T}{T} = d_2 \qquad (6.8)$$
$$s_3 = \frac{d_3 T}{T} = d_3 \; .$$

Substituting Equation (6.8) into Equation (6.7) gives

$$V_s = V_c 1$$
$$I_1 = I_p - d_3 I_p$$
$$V_c 1 = \frac{(1 - d_1 - d_3) V_{co}}{1 - d_3} \qquad (6.9)$$
$$\frac{V_{co}}{R_L} = (1 - d_1 - d_3) I_p$$
$$V_{co} = R_L I_L \; .$$

The effective resistance for the boost can be defined as

$$R \quad = \frac{V_s}{I_1} \; .$$

Using the steady state equations, the equivalent resistance in terms of the duty cycle and the load resistance can be found as follows:

Therefore, for a boost converter, the effective resistance can be written as

Referring to Figure 6.1, and assuming that the converter is operating in discontinuous conduction mode (meaning that the current in the inductor becomes zero for a time) then, when the boost converter is operating in mode one, the current i_p (t) rises linearly from a zero value at the beginning of the mode to a maximum value at time t=d_1T of

The converter will then switch into mode two operation and the current will fall linearly from I_{pmax} to a zero value at a time t= (d_1 + d_2

so Equation (6.19) may be written as

Rearranging Equation (6.21) gives

Therefore

In terms of d_3 , the solution may be written as

If the solution for d_3

At the boundary condition between continuous and discontinuous conduction mode, d_3 is equal to zero. Solving Equation (6.24) in terms of the inductor L_p at the boundary condition gives

It can be seen from Equation (6.25) that when d of the solutions for a minimum L_p , and the duty cycle which is most likely to cause discontinuous condution mode is 1/3. Substituting this value back into Equation (6.25) and simplifying gives

$$L_p = \frac{T\ R_L}{2}(.1481) = \frac{2}{27} T\ R_L\ . \qquad (6.27)$$

Thus, to ensure that the boost converter is always operating in continuous conduction mode, a good rule of thumb is that

$$L_p - \frac{2}{27} T\ R_L\ . \qquad (6.28)$$

In the steady state analysis of the boost converter presented in this thesis, only the continuous conduction mode was considered. Thus, d_3 is equal to zero and Equation (6.12) may be written as

$$R_{effbst} = R_L (1 - d_1)^2\ . \qquad (6.29)$$

Equation (6.29) represents the equivalent resistance at the output of the rectifier and is equivalently the same as the value R_o given in Equation (4.31). Substituting Equation (6.29) into Equation (4.31) gives

$$R_{effbstrec} = \frac{\pi^2 R_L (1 - d_1)^2}{12} \quad . \tag{6.30}$$

The equation given in (6.30) will be used to predict the performance of the IPM feeding the rectifier-boost topology.

From the result given in Equation (6.29) it can be seen that, as the duty cycle is changed, the Thevinin equivalent is not constant; therefore, one cannot assume a constant resistive load model. For an **ideal** voltage source supplying the boost converter, the implications of this may not be that substantial; however, for a “weak” autonomous power supply, such as the permanent magnet machine used in the experiments described in this thesis, the effect is that the generator will “see” a nonlinear resistor which changes as the duty cycle of the converter is changed. Since the value of the impedance presented to the IPM machine will change the voltage output of the generator, the boost converter may not necessarily raise the load voltage.

6.1.2 Examination of Ideal Boost Converter

In order to gain an appreciation of the significance of Equation (6.29), various graphs are generated with the assumption that the dc voltage into a boost convertor is a constant 10 volts dc, and the load resistance is a constant 10 ohms.

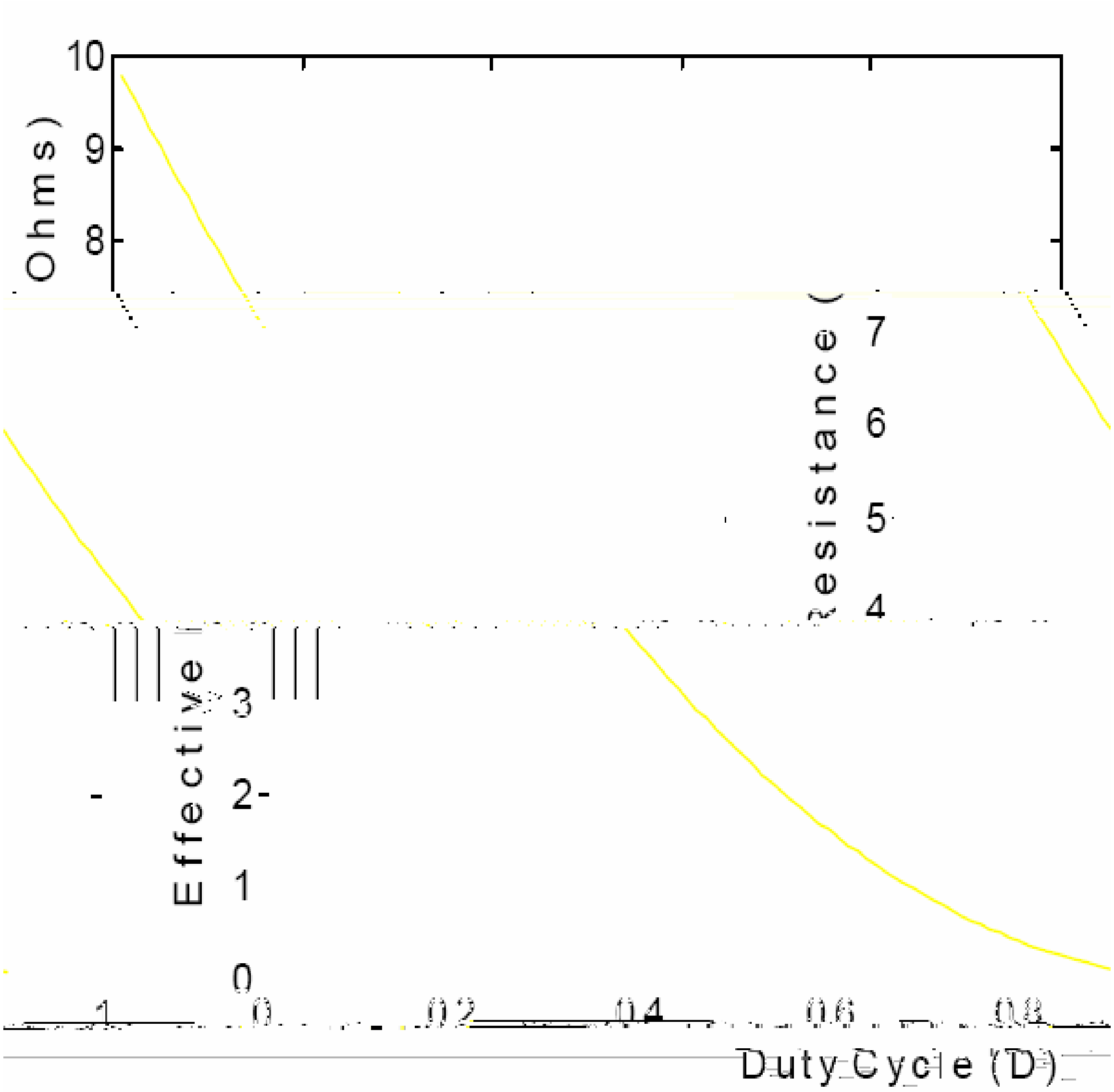


Figure 6.5. Effective resistance vs duty cycle for a boost converter

Figure 6.6 shows how the input current increases as the duty cycle increases. This is perfectly understandable since the load demand increases as the effective resistance decreases. It can be seen that there is an exponential rise in the load current which would tend towards infinity as the duty cycle approaches 1.

Figure 6.7 shows the exponential rise in input power into the system as the duty cycle increases. This rise, is of course, caused by the exponential rise of the input current.

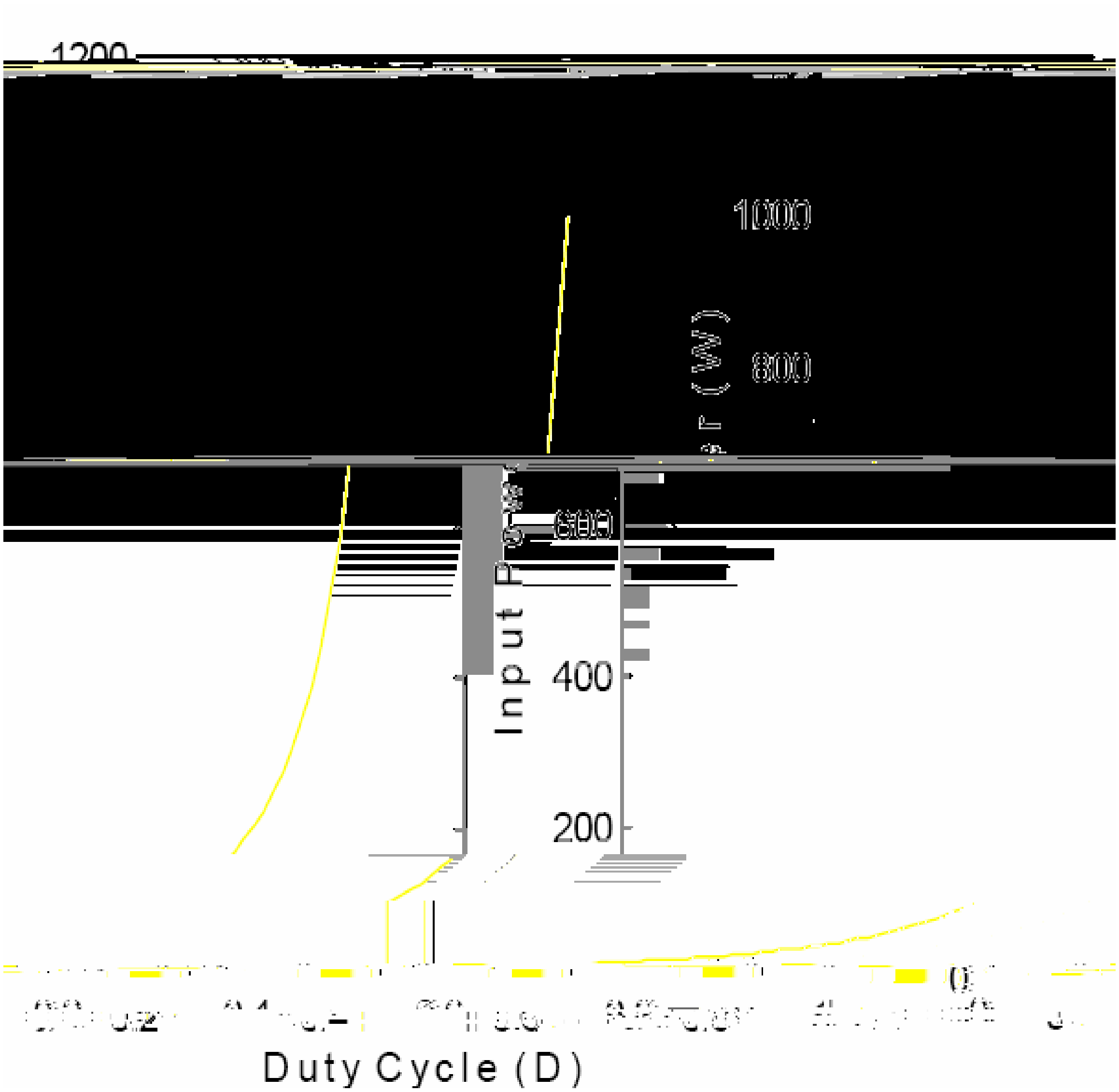


Figure 6.7. Input power vs duty cycle for a boost converter

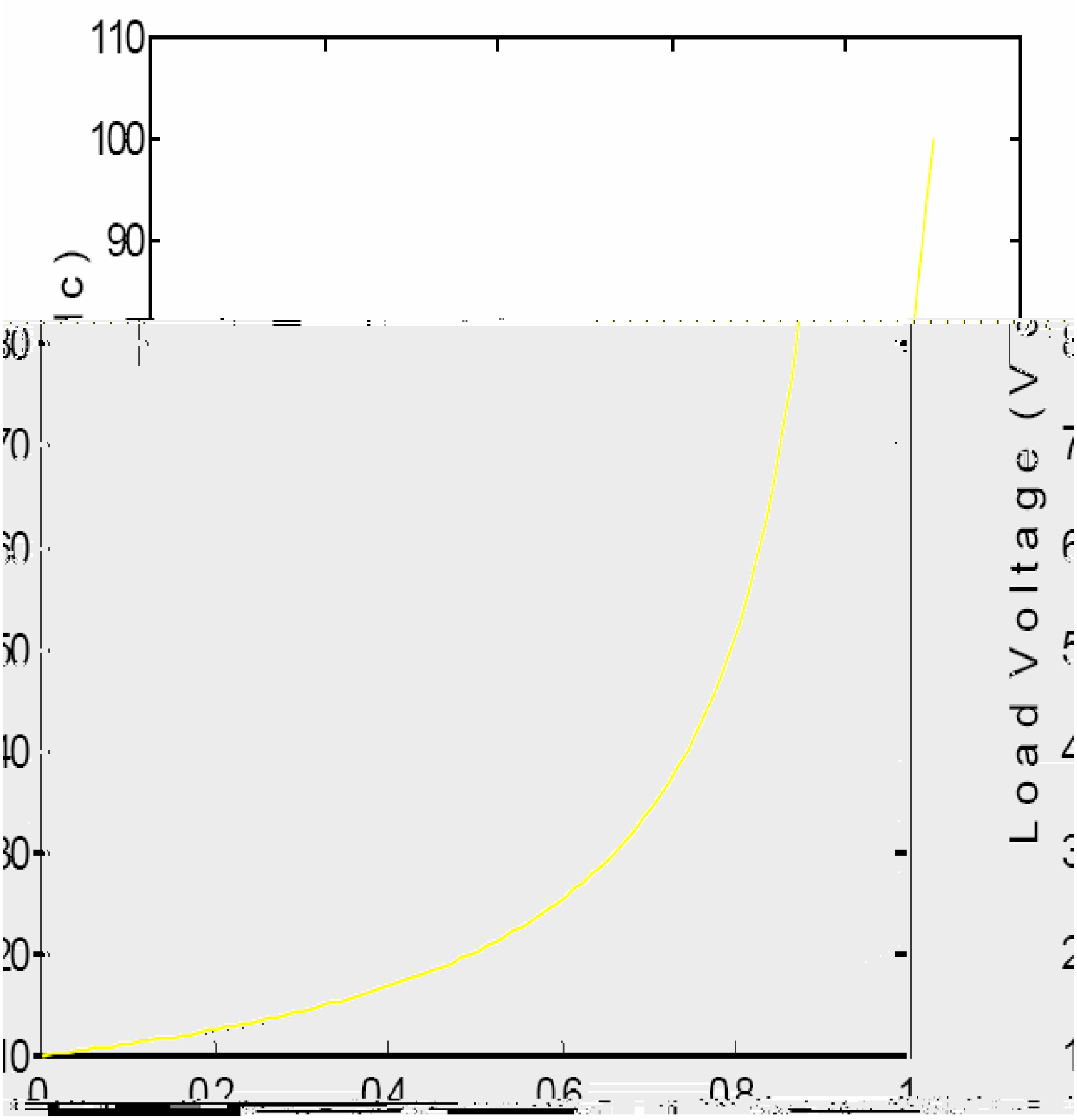


Figure 6.8. Load voltage vs duty cycle for a boost converter

Figure 6.8 displays the intended effect of the boost converter topology, that being to increase the voltage above the supply voltage. It can be seen from Figure 6.8 that the load voltage at a duty cycle of 0.8 is approximately 5 times the 10 volt constant dc source voltage.

6.2 Steady State Performance of an IPM Generator Feeding a Rectifier-Boost-Resistive Load

6.2.1 Introduction

In this section, the measured steady state performance of the IPM generator feeding a rectifier-boost-resistive load will be compared with the predicted performance of the system. In order to obtain a full performance curve (meaning that the performance of the IPM generator is tested for loads ranging from a light load to a large load) for the boost converter, it is not the load resistance R_L which is varied from a small to a large value. Rather, it is the duty cycle D which is varied from 0 to almost 1.

Referring to Figure 6.5, and remembering that the actual load resistance for this graph was 10 ohms, it can be seen that the largest resistance which the generator will see is the actual load resistance $R_{L.}$ Thus, if one wants to be able to study the boost system operating under a light load, a large load resistance must be chosen. As the duty cycle is increased from zero, the effective resistance decreases and, therefore, it is possible to test the topology under the condition when the IPM generator is feeding a large load.

The load resistance chosen to test the system was 88 Ω and the system was tested for the generating frequencies of 30 and 45 Hz. The values of the rectifier filter components were L_d = 9.3 mH and C_1 = 10mF. The values of the boost filter were Lp = 10 mH and C_o = 10mF.

Figures 6.10 and 6.11 show how the generator voltage and rectifier voltage (which is a function of the generator voltage) behave as the duty ratio increases. The rectifier voltage is the dc source to the boost converter and it is clear to see that, as the duty ratio is changed, this dc supply voltage is not constant. ths dc sup tTJ19.IEei TDo/T3e3s2urc9 Tc- -37s285 Tsa.pv867 Tw(t

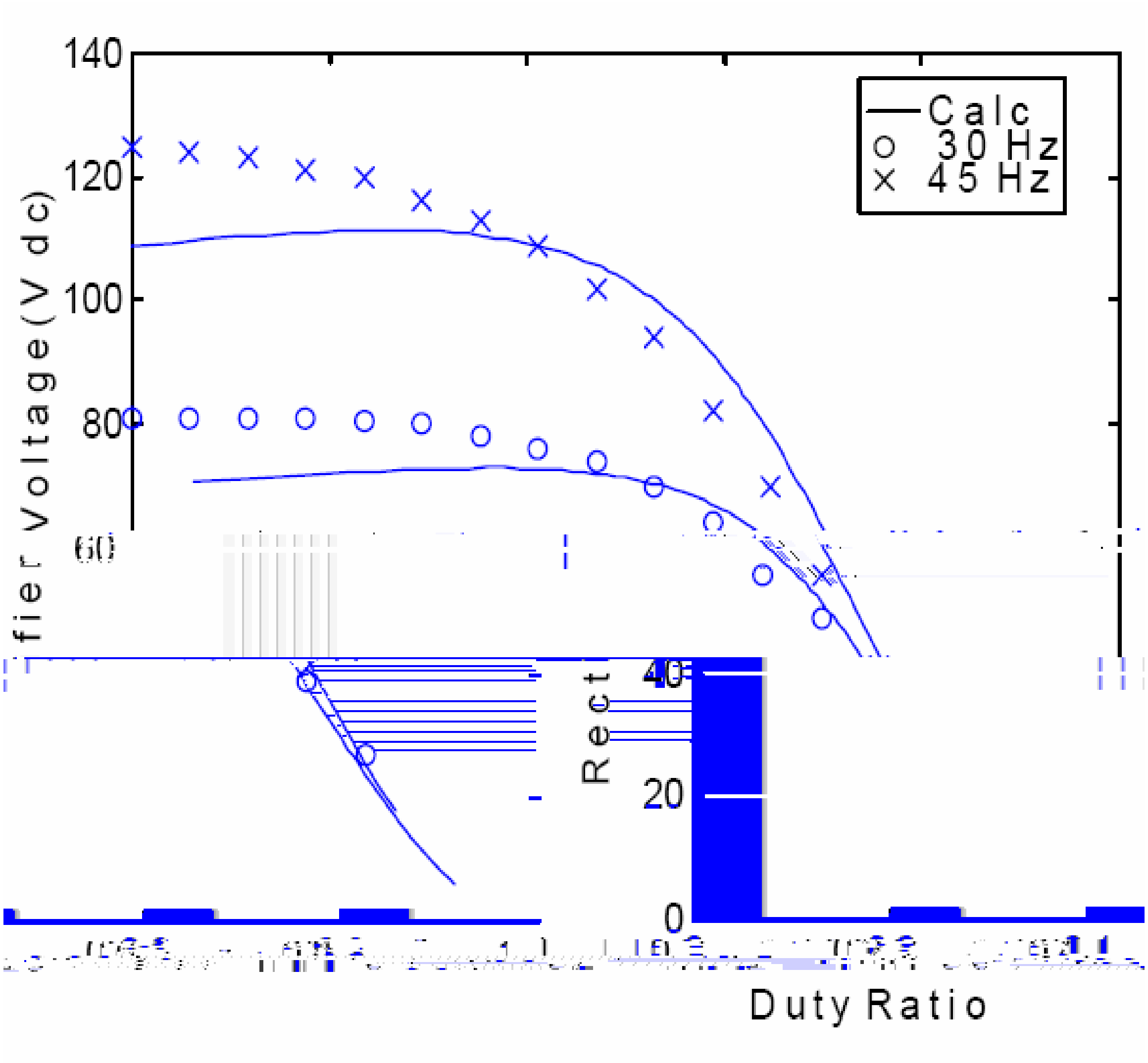


Figure 6.11. Measured and calculated rectifier voltage vs duty ratio for IPM generator feeding rectifier-boost-resistive load

Figure 6.12 plots the generator output power vs the duty ratio. It can be seen that the maximum power produced at 45 Hz occurs when the duty ratio is approximately 0 .6, and,

6, aPis appr1oTJ29.8258 iximm6power6(8.5(6pd at 45TJ19.8-2.3220.361Tc-0.060974)-0.7(xs wa appro assumption that the input voltage into the boost is constant. As Figures 6.9 and 6.10 demonstrate, this assumption is not valid for the IPM generator feeding the system.

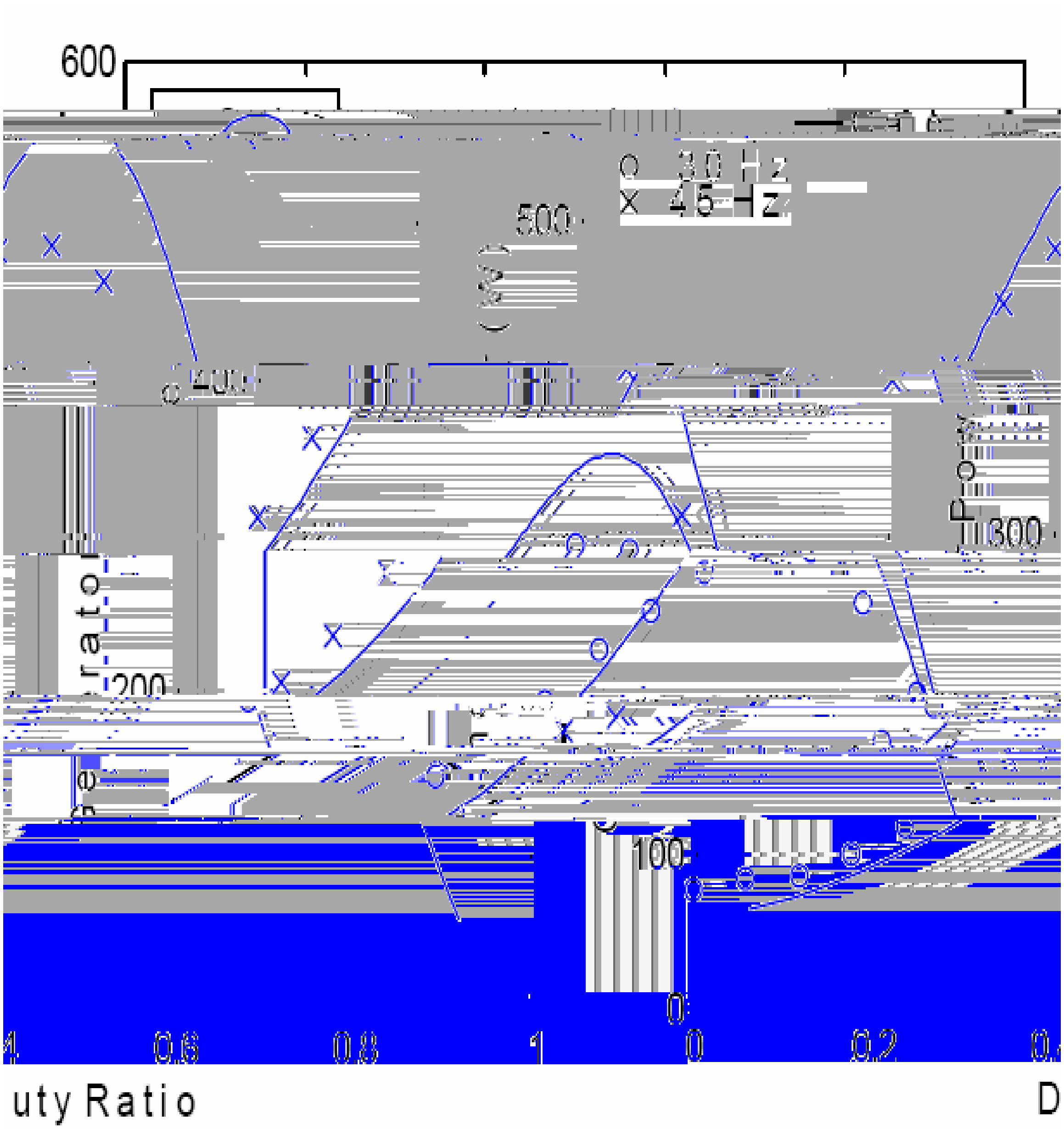


Figure 6.12. Measured and calculated generator output power vs duty ratio for IPM generator feeding rectifier-boost-resistive load

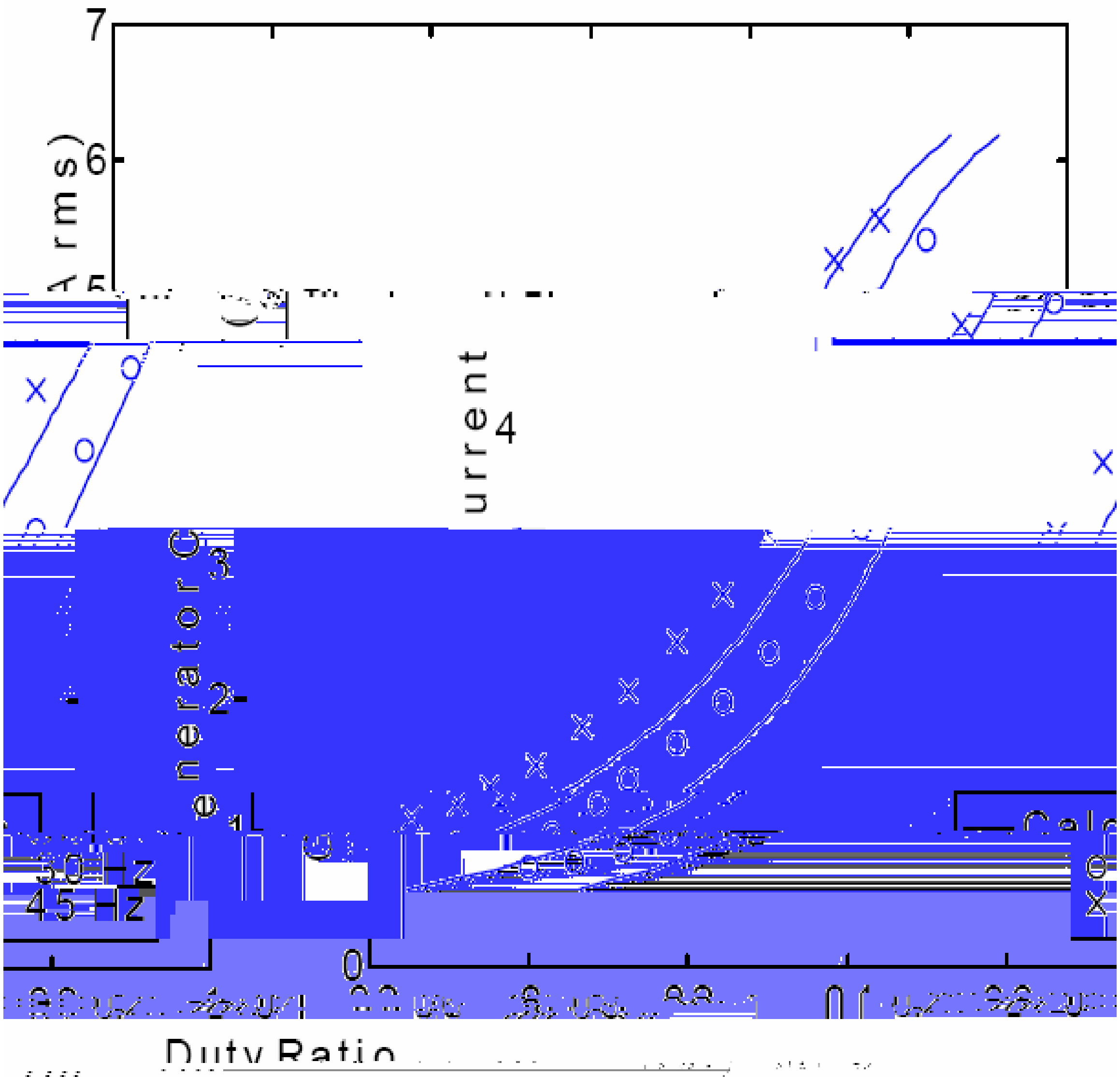


Figure 6.13. Measured and calculated generator current vs ratio for IPM generator feeding rectifier-boost-resistive load

The graph shown in Figure 6.13 plots how the generator current increases as the duty cycle is increased. There is an exponential rise in the current up to the points where the maximum power occurs (duty cycles of 0.6 and 0.65 for frequencies of 45 and 30 Hz respectively), however, after the maximtor

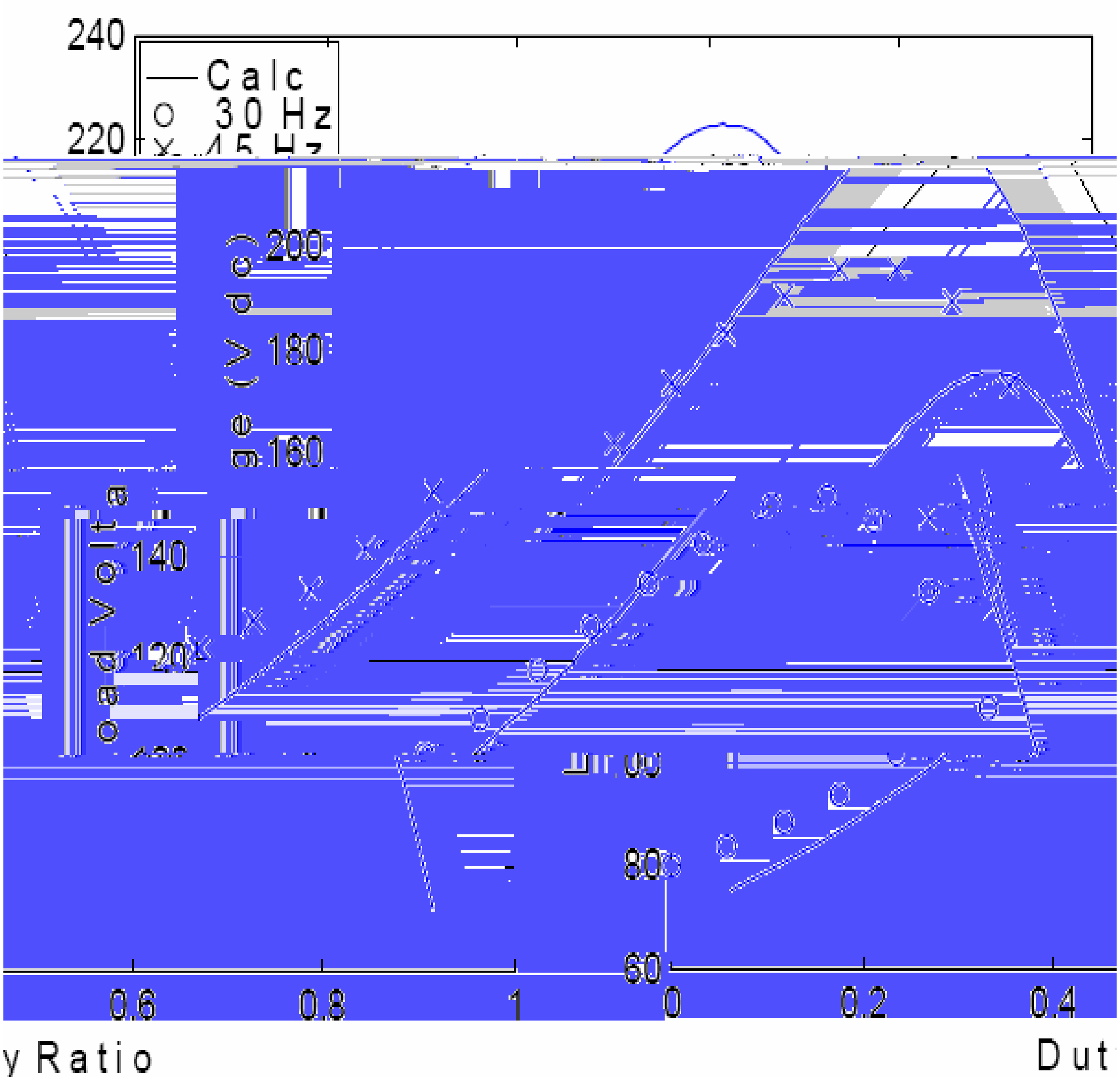


Figure 6.14. Measured and calculated load voltage vs duty ratio for IPM generator feeding a rectifier-boost-resistive load

The measured and calculated load voltage vs duty ratio is shown in Figure 6.14. Remembering that for an ideal boost converter (see Figure 6.8) the load voltage will increase exponentially as the duty cycle is increased, it can be seen in Figure 6.14 that the IPM-rectifier-boost-resistive load topology behaves like an ideal boost converter up to the maximum power point, but after the maximum power point the load voltage actually decreases. A decrease in load voltage as the duty cycle is raised is probably not the outcome intended when a boost converter is introduced into the system. Therefore, for a practical operating scheme, the duty cycle may be restrained from going above the maximum power point.

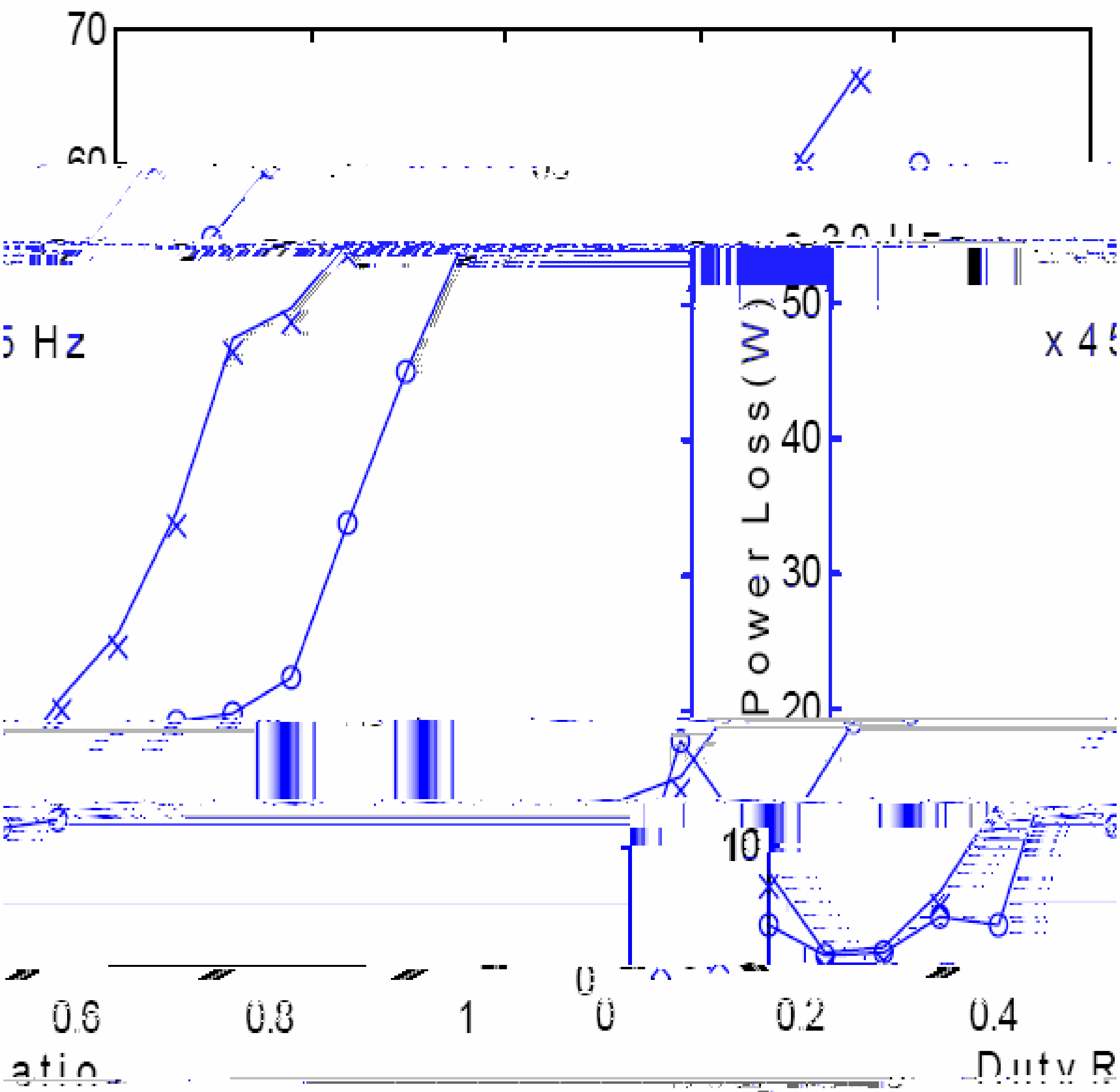


Figure 6.15. Measured power loss of rectifier-boost system vs the duty ratio

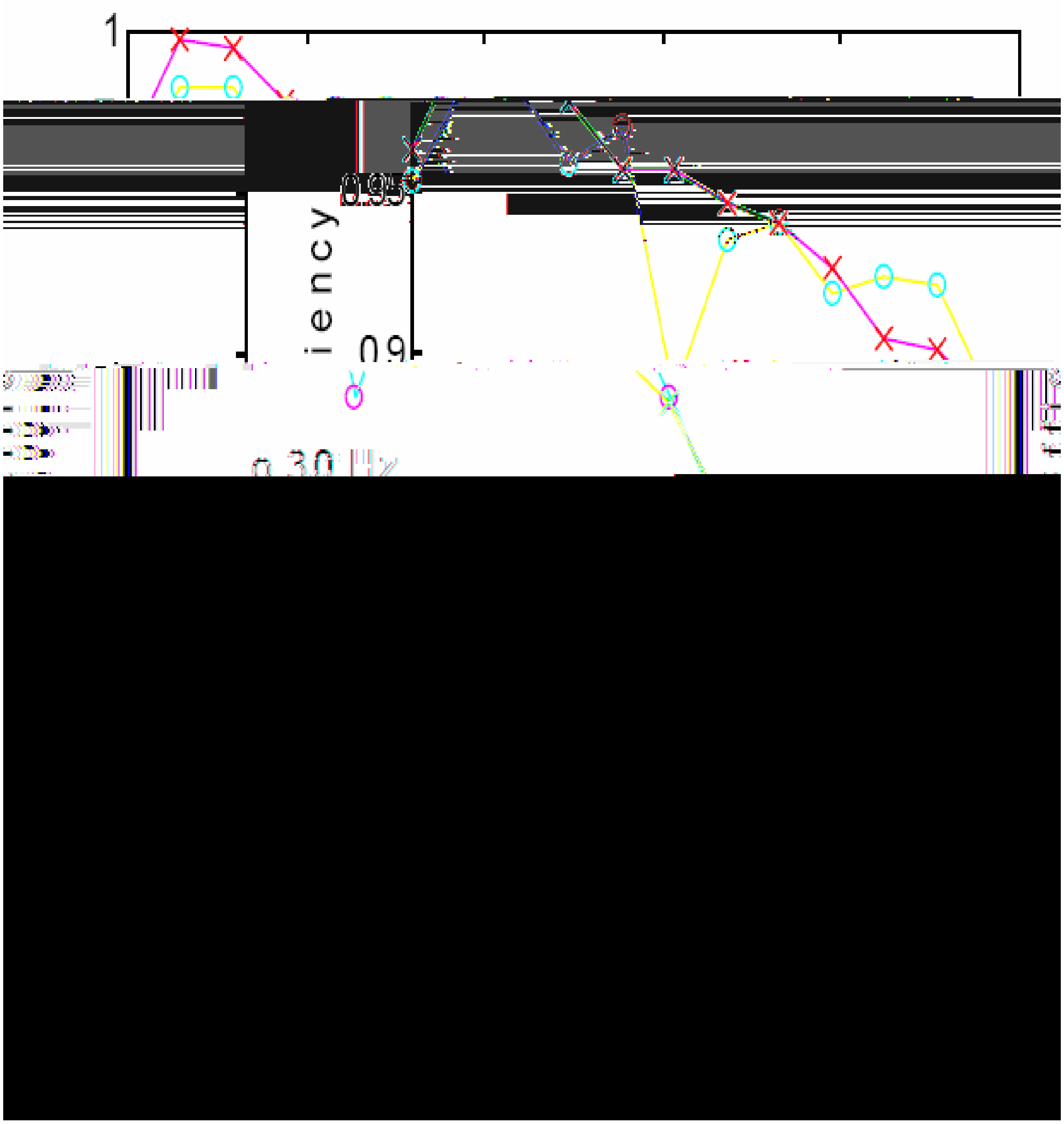


Figure 6.16(a). Measure converter efficiency vs duty ratio for IPM generator feeding a rectifier-boost-resistive load

Up to the duty cycle corresponding to the maximum power point, the topology is demonstrating a very good ability to control the load output voltage even though the generator voltage is changing. For example, at 45 Hz operation, even though the generator line to neutral terminal voltage drops from approximately 55 Volts at zero duty cycle to approximately 36 volts (see Figure 6.9) at a duty cycle of 0 .6, the load voltage continues to increase.

Also, assuming that the duty cycle is not constrained at some maximum value, then, Finally, Figure 6.16(b) plots the measured and the calculated effective resistance vs the duty cycle for both operating frequency. It is a bit of a misnomer to refer to the "measured" effective resistance since it is not the effective resistance which is measured; rather it is the actual load resistance which is measured and the corresponding effective resistance is calculated from this value.

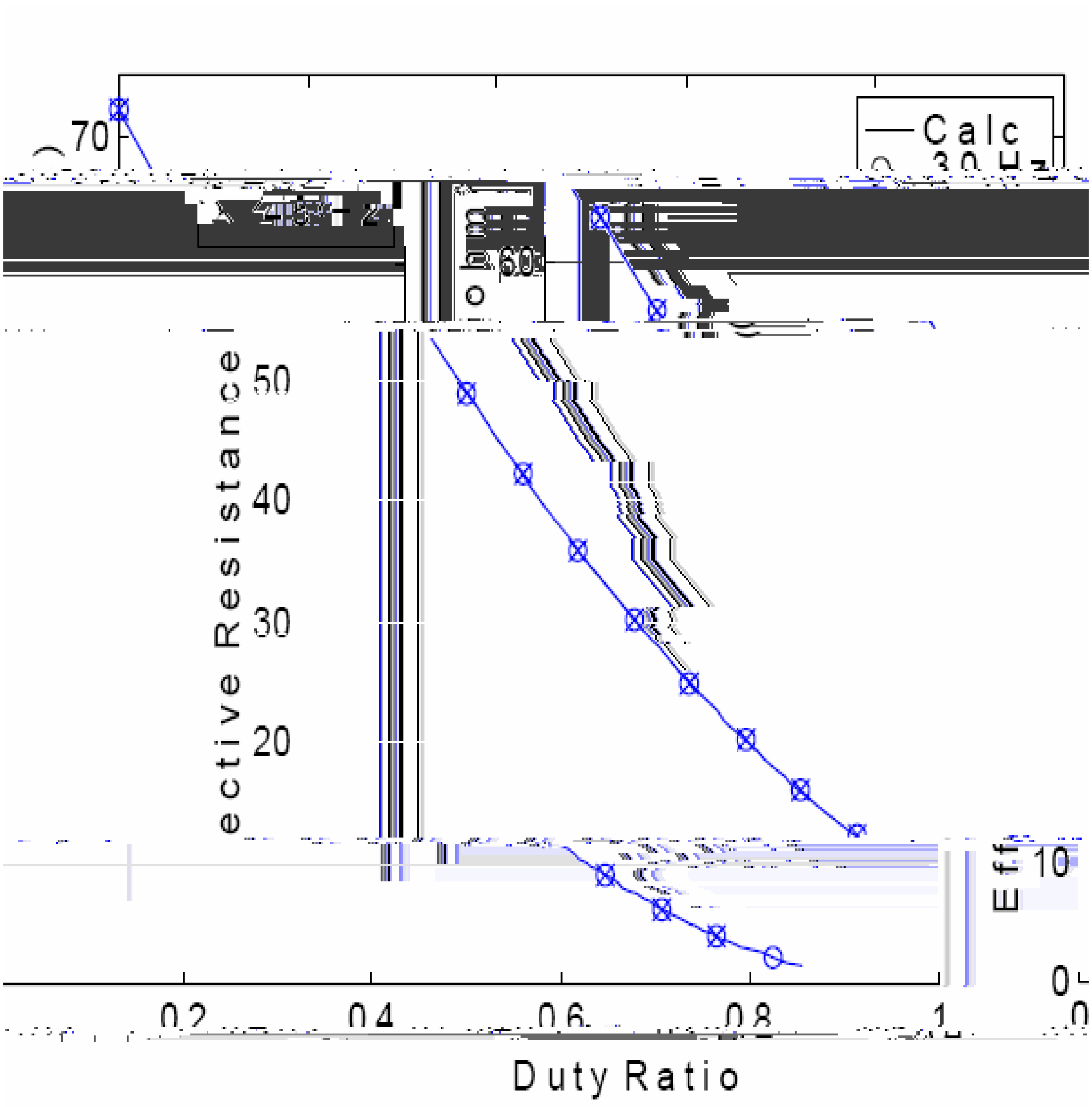
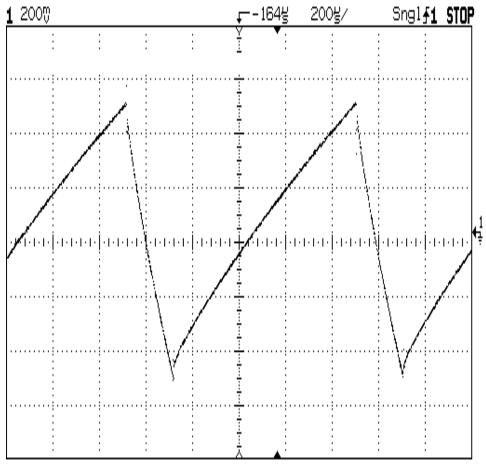
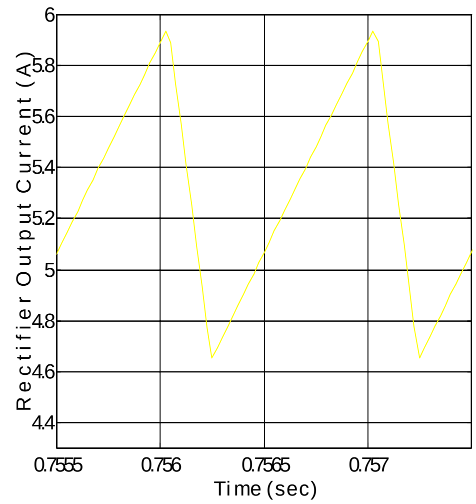


Figure 6.16(b). Measured and calculated rectifier-boost effective resistance vs duty ratio

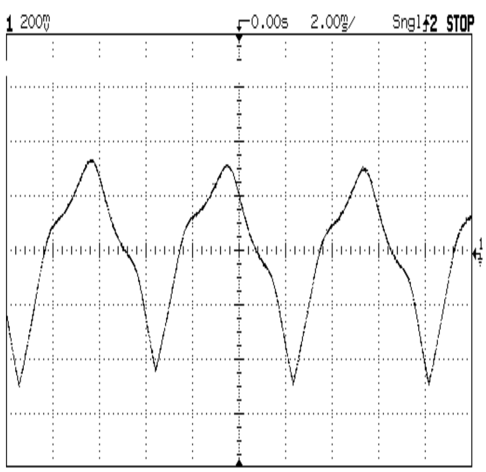


Measurement

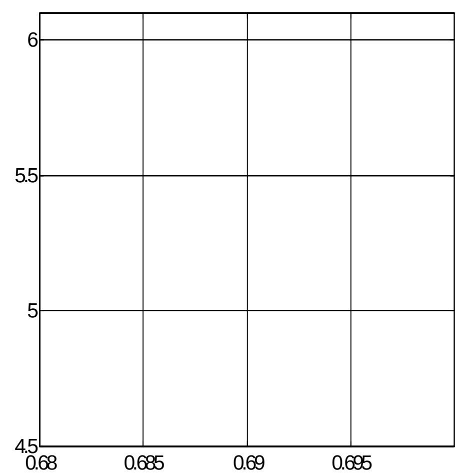


Simulation

Figure 6.19. Measured and simulated boost inductor current waveforms for the generator feeding a rectifier-boost-resistive 77Ω resistive load. Rotor speed=900 rpm. Measured waveform scale: current: .2A/div, time .2ms/div



Measurement



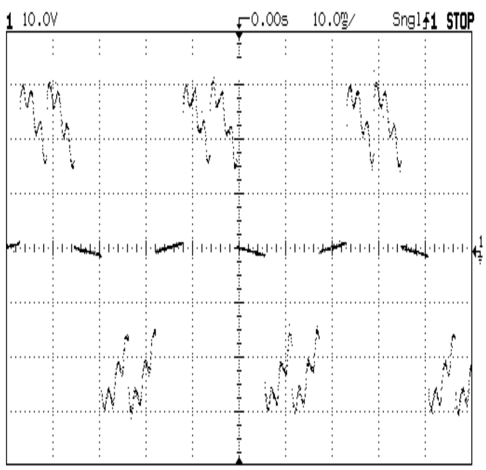
Simulation

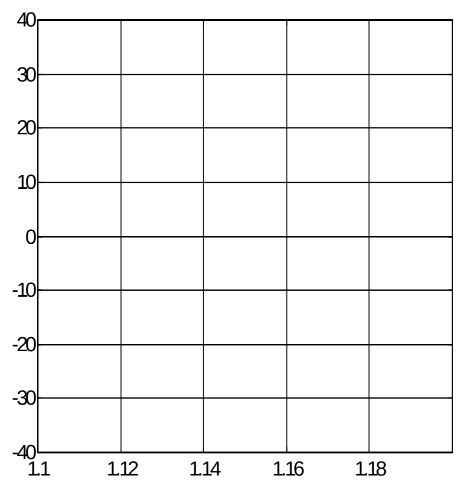
Figure 6.20. Measured and simulated rectifier output current waveforms for the generator feeding a rectifier-boost-resistive 77 Ω resistive load. Rotor speed=900 rpm. Measured waveform scale: current: .2A/div, time 2ms/div

continuous conduction mode. Figure 6.20 shows the measured and simulated current through the rectifier filter inductor L_d .

6.3.2 Boost Converter in Discontinuous Conduction Mode

In this section, the inductor L_p is changed from the value of 10mH used in section 6.3.1 to the value of 0.25mH. In addition, the duty cycle is changed from 0.80 to a value of 0.5. With these changes, the boost converter no longer operates in continuous conduction mode; rather, it operates in discontinuous conduction mode.

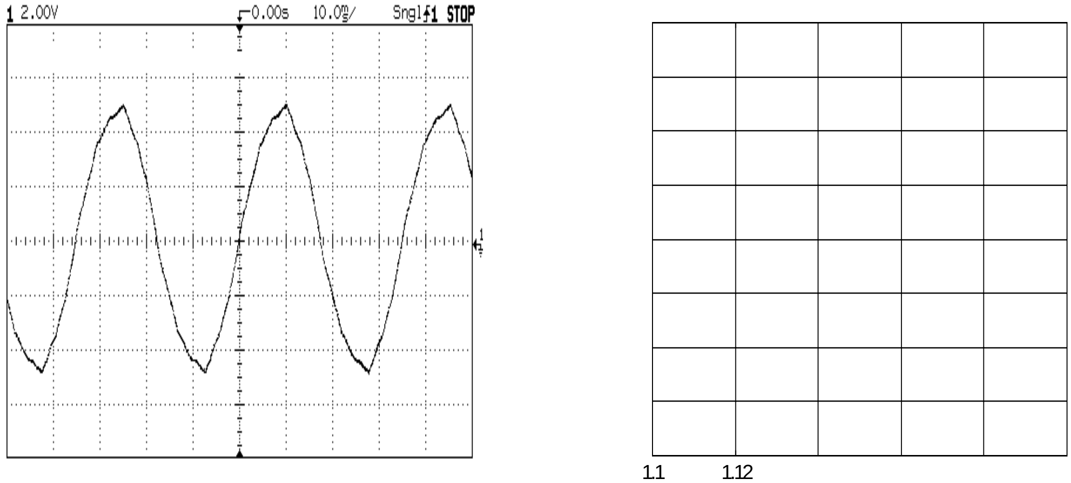




Measurement

Simulation

Figure 6.21. Measured and simulated generator line to line voltage waveforms for the generator feeding a rectifier-boost-resistive 77Ω resistive load. Rotor speed=900 rpm. Measured waveform scale: voltage: 20v/div, time 10ms/div

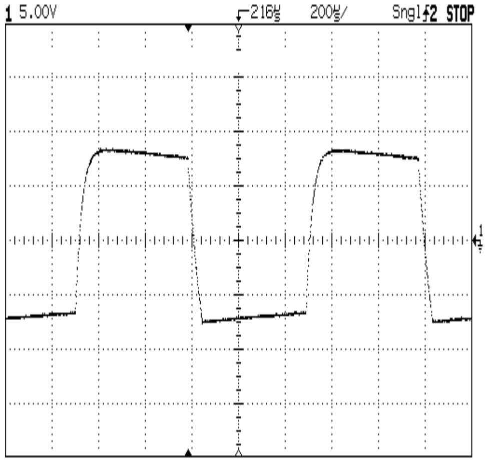


Measurement Simulation

Figure 6.22. Measured and simulated generator line current waveforms for the generator feeding a rectifier-boost-resistive 77Ω resistive load. Rotor speed=900 rpm. Measured waveform scale: current: 2A/div, time 10 ms/div

Figures 6.21 and 6.22 show the measured and simulated line to line voltage and line Current of the generator. The simulated and measured waveforms of the voltages and currents compare favorably with each other in both magnitude and form.

It can be seen in Figure 6.23 that the converter is clearly operating in discontinuous conduction mode. As was done concerning the buck converter, it is also worthwhile to note the difference in the current in the measured waveform of Figure 6.23 (where the converter is in discontinuous mode) to the measured current of Figures 6.19. When the converter is in discontinuous mode, it can be seen that both the peak current and the change in current from its minimum to maximum value is much larger than when the converter is operating in continuous conduction mode. The high stresses placed on the transistors due to the large

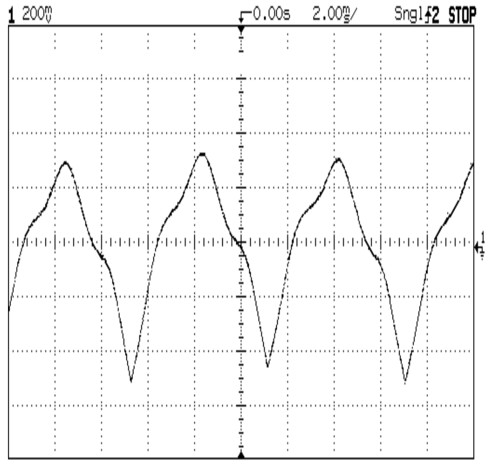


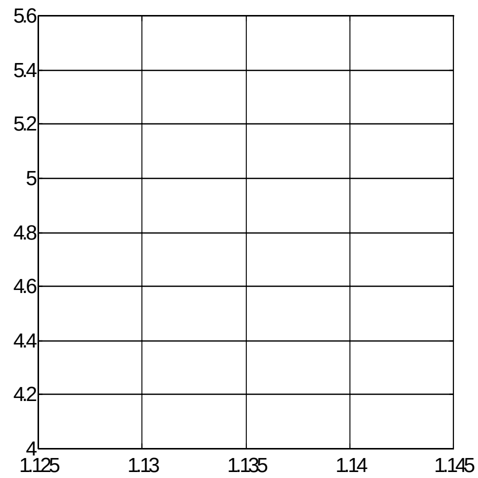
Measurement Simulation

Figure 6.23. Measured and simulated inductor current waveforms for the generator feeding a rectifier-boost-resistive 77Ω resistive load. Rotor speed=900 rpm. Measured waveform scale: current: 5A/div, time .2ms/div

currents and large rate of change in currents (di/dt) is one of the main reasons why, for practical designs, the discontinuous mode of operation is normally avoided.

Finally, Figure 6.24 shows the measured and simulated current waveforms through the rectifier filter inductor L_d. The simulation is fairly close to the measured value.





Measurement Simulation

Figure 6.24. Measured and simulated rectifier output current waveforms for the generator feeding a rectifier-boost-resistive 77Ω resistive load. Rotor speed=900 rpm. Measured waveform scale: current: .2A/div, time 2ms/div