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Modeling of Boost Converter-based Electronic Load with Energy Recycling Capability

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Abstract – **Modeling and control of an active electronic load with energy recycling capability is presented in this paper. The system is composed of a boost DC-DC converter and a grid-connected signal phase inverter. The boost converter control system follows the input current reference set by the user, while the inverter control system maintains a constant DC-link voltage by controlling the current injected into the grid. The grid current harmonic content is filtered by an LCL filter. The model of the converters and the control system is implemented in MATLAB/Simulink. Simulation results demonstrate the proper operation of the conversion system.**

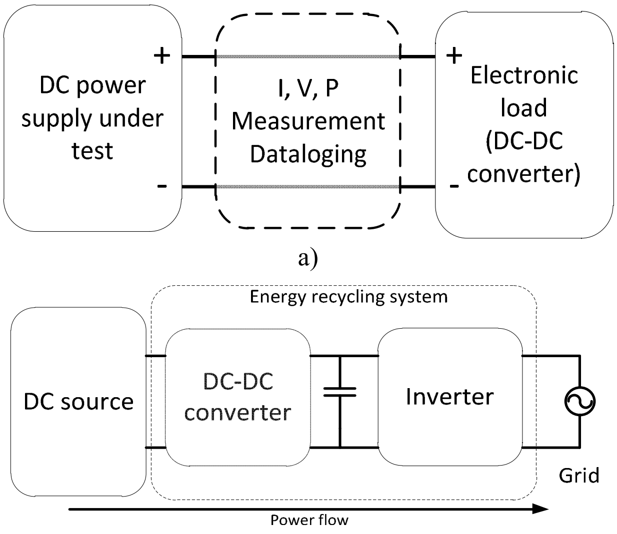
Keywords – **Electronic load, energy recycling, grid-connected, single-phase.**

I. INTRODUCTION

Active electronic loads are used for testing and characterization of power supplies and sources such as PV arrays, fuel cells, battery banks etc. Power electronic converters have considerable advantages as compared to passive load banks: compact volume and weight, precise control, possibility of data acquisition during the test procedure [1-4] (FigFig.1-a).

Complex structures, composed of a DC-DC converter and a grid-connected inverter are capable of energy recycling: injecting power into the grid while testing a DC power source (Fig.1-b) [5]. An electronic load with energy recycling is an interesting type of test equipment, which can be programmed to simulate a variety of load characteristics, including non-linear behavior and transients. In comparison to traditional passive load devices, more than 80% of the energy would be returned to the grid. With the addition of a rectifier in the structure single or three-phase AC electronic loads can be constructed. These are often used for testing of active power filters and power conditioners in low-voltage grids or testing the stability of autonomous micro and nano-grids. With proper design of the filters, the converters and their control it is possible to feed energy back to the grid with a small loss and high power factor [5, 6]. The active regeneration scheme allows for a reduction of passive components and the cooling system. For instance, [2] presents a three-phase AC electronic load for testing of distribution network stability that is able to sink as much as 50kVA instantaneous power. A 3-phase regenerative electronic load to test shunt equipment such as active power filters and power conditioners at high power levels is presented in [3]. The electronic load is composed of the two inverters with a common DC bus.

In order to ensure proper design of the converters, modelling and simulation of their behavior should be performed. This paper presents the modelling and simulation of a DC electronic load with energy recycling capability. The structure comprises a boost DC-DC converter and a single phase grid-connected inverter (Fig.2). The boost converter control system follows the input current reference set by the operator, while the inverter control system maintains the DC-link voltage at the reference value (350V) by increasing or decreasing the grid current. In this way all the power drawn from the device under test, except of the losses, is injected into the grid. The undesirable high frequency ripple and harmonic content of the grid current is filtered by an LCL filter.



a)

b)

Figure 1. Electronic load for testing of DC power sources
a) by a DC-DC converter-based electronic load,
b) by energy recycling

II. MODELLING OF THE CONVERSION SYSTEM

Various topologies of DC converters can be used as a controllable load: Boost, inverting buck-boost, Sepic, Ćuk or isolated converters such as the flyback, bridge or push-pull [3-11]. Among the transformerless converters the Sepic and Ćuk are more complex than the boost or buck-boost ones in terms of circuit design and they do not possess considerable advantages as compared to the boost or buck-boost converters for this application. If used as a stand-alone electronic load, the buck-boost is the only transformerless converter that can simulate a variable resistance from near zero up to a near-infinite value.

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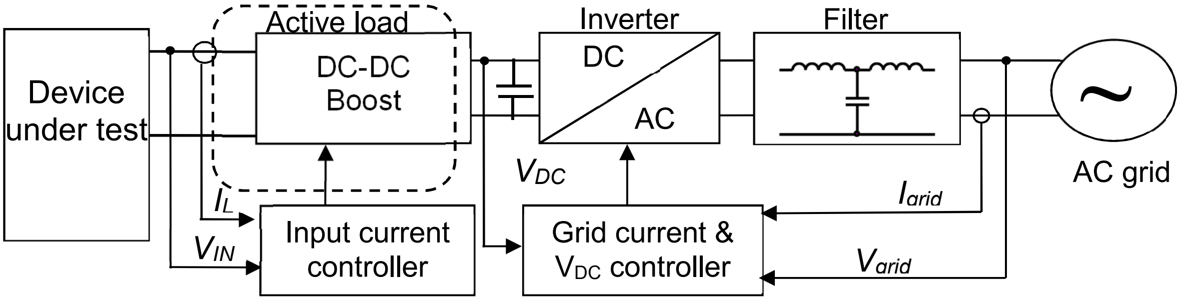


Fig. 2. Structure of the active load with energy recycling

A. Boost converter model

The minimal resistance that a boost DC-DC converter can simulate is determined by the resistance connected at the converter output. But in the case when power is injected into the grid, a boost converter can also simulate a near-zero resistance, because power is transferred through the DC-DC converter, the DC-link capacitor and the inverter into the grid. The smallest resistance that such a system can simulate is determined by the equivalent resistances of the circuit components (Fig.2).The boost converter is necessary in order to increase and stabilize the inverter input voltage to ensure its correct operation. The converter circuit is presented in Fig. 3. The switch can be a bipolar transistor, MOSFET, IGBT or other transistor with the appropriate characteristics. In this study it is modelled by an idealized switch with instantaneous reaction and zero internal resistance.

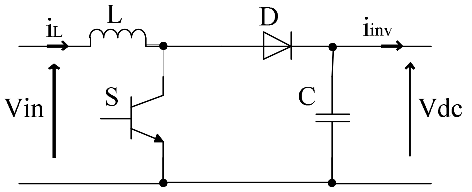


Figure 3. The boost DC-DC converter circuit.

The DC-DC converter operates at constant switching frequency (20kHz) and is current-controlled (the current reference i_{Lref} and the current i_L is the current drawn from the DC source under test. The control structure can also be configured to operate with a power reference (by assuming that the voltage drop of the DC source is not considerable) In this case the boost converter control system is similar to the Limited Power Point tracking of a PV array [11]. The DC-DC converter control (current reference) is depicted in Figure 4. The current reference i_{Lref} is set by the operator. The measured input current of the DC-DC converter is subtracted from this reference and the difference is passed to a PI regulator. Then, the converter control signals are obtained using PWM. In this study a carrier frequency of 10 kHz is chosen.

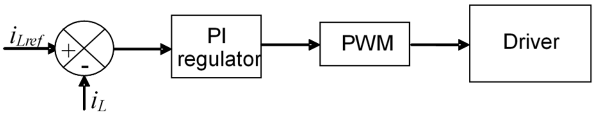


Figure 4. Boost converter control system

The equations for the inductor current and the capacitor voltage are used for modelling the boost converter by its switching function [2], [3]:

$$\left|\begin{array}{l} \dfrac{di_L}{dt} = \dfrac{1}{L}\left[V_{in} - (1-d)V_{dc}\right] \\ \dfrac{dV_{dc}}{dt} = \dfrac{1}{C_{DC}}\left[(1-d)i_L - i_{inv}\right] \end{array}\right. \qquad (1)$$

where i_L is the inductor current, L is the inductance, V_{in} is the converter input voltage, d is the switch duty ratio, V_{dc} is the converter output voltage, C_{DC} is the converter output capacitor (the DC-link capacitor from Fig.2) and i_{inv} is the inverter input current.

The boost converter model, implemented in MATLAB/Simulink uses the source voltage V_{in} and the inverter current i_{inv} as input variables and the calculated input current i_L and output voltage V_{dc} are the model output variables.

B. Modelling of the single phase inverter

The bridge inverter circuit is presented in Fig. 4. The grid filter is LCL with the following values of the elements: L_1=10mH, C=22μF and L_2=2mH.

The DC-link capacitor C_{DC} is common for the boost converter output and the inverter input. An insufficient value of this capacitor results in poor system stability and an excessively large capacity affects the system dynamic response. A value of C_{DC}=2200μF is considered in this study. The inverter is control consists of two loops: the first loop is responsible for maintaining the voltage at the inverter input (V_{DC}) constant and a second loop controls the current supplied to the grid.

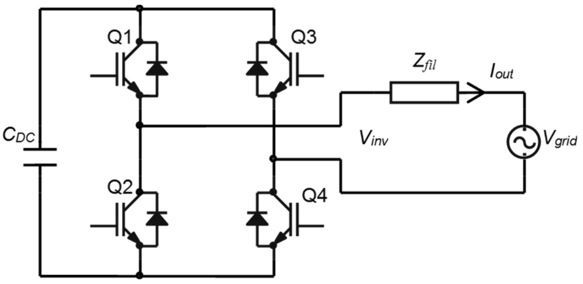


Figure 4. Single phase grid-connected bridge inverter circuit.

Several approaches for PWM control of a grid-connected inverter exist: hysteresis current-mode control is often used due to its ease of implementation and robustness. Disadvantages of this control approach are the variable switching frequency, which can become too high if the desired current ripple is low, increased losses and strong dependency on the system parameters and controller tuning

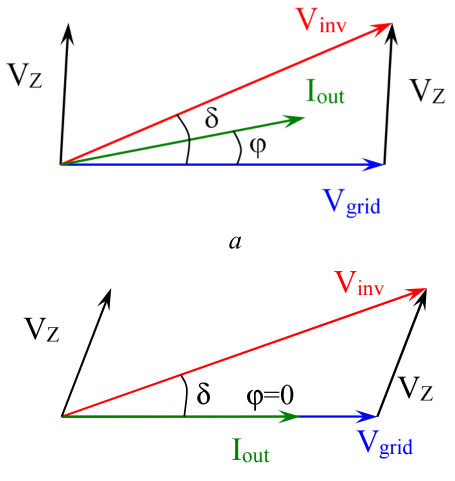
[10]. The ease of hardware implementation of this method is not an advantage anymore – most contemporary microcontrollers have enough computational power to perform complex PWM methods like space vector modulation.

Therefore, a voltage vector-controlled PWM approach is chosen for this study. In order to feed current into the grid it should have a phase angle of less than 90° from the grid voltage. This is the case when the inverter output voltage is phase-shifted ahead of the grid voltage. At power levels less than several hundred watts, the impedance between the inverter and the grid should be taken into account (due to equivalent series and parallel impedances in the circuit and filter elements, the non-zero active resistance of the conductors, the switches etc.) In this case the current supplied to the grid is determined by the voltage drop on the impedance $\dot{Z}$ and by the difference between the two voltages:

$$V_Z = V_{inv} - V_{grid} \tag{2}$$

$$I_{out} = \frac{V_{inv} - V_{grid}}{Z} \tag{3}$$

where V_Z is the voltage drop over the impedance Z, V_{inv} is the RMS value of the first harmonic of the modulated inverter output voltage and V_{grid} is the grid voltage. The phasor diagram corresponding to (2) and (3) is illustrated in Figure 5-a. The phase angle between the current *Iout* and V_Z is less than 90° because of the predominant inductive character of impedance *Z* and there is an angle $\varphi \neq 0$ between the grid voltage and the current fed into the grid. Knowing voltage drop *Vz* we can control voltage *Vinv* in such a way that the current supplied to the grid is in phase with the grid voltage (the phasor diagram in this case is presented in Figure 5-b). By using this control method it is also possible to feed reactive power to the grid in order to compensate for the reactive power of other loads connected at the same node.



a

b

Figure 5. Phasor diagram of the voltages and currents of the single-phase inverter.

The grid-connected inverter requires a grid voltage so that it can synchronize with it and inject power into the grid. The synchronizing unit can form a reference sine wave signal by two approaches [11]. One way to do this is by using directly the grid voltage (after converting its amplitude to a lower value). This way is simple and reliable, although it has an inconvenience: it is possible that the grid voltage at the coupling point contains some distortions, parasite signals and other defects. The second method is to use a Phase locked loop (PLL). The PLL detects the zero crossing of the grid voltage and then produces a clean sinusoidal signal with permanent amplitude and in phase with the grid [6]. In this work, a PLL-based method for synchronization is used and implemented into the model.

III. SIMULATION RESULTS

The system is modeled in the MATLAB/Simulink environment. Both converters are modeled by their switching functions with idealized switches. The Losses in the DC-link capacitor are modeled by equivalent parallel and series resistances.

The boost converter controller is first tested in steady-state by different values of the current reference in order to assess its precision. The results are presented in Table 1. The simulation results demonstrate the proper operation of the converter and precise control of the input current.

TABLE 1. STEADY STATE PERFORMANCE OF THE BOOST CONVERTER CURRENT CONTROLLER

I_{L_ref}, A	I_L, A	Error, %
1	1,01	0,1
2	1,99	0,5
3	3,02	0,67
4	4,01	0,5
5	5,05	0,1
6	6,03	0,5
7	7,05	0,7
8	8,09	0,1
9	9,1	0,1
10	10,1	0,1

The energy recycling capability of the system and the grid current controller performance is assessed by simulation with a variable current reference. Figure 6 presents the DC-link voltage V_{DC}, power and current injected into the grid – I_{OUT} and P_{OUT}. The simulation results demonstrate the proper operation of the conversion system: the DC-link voltage is maintained stable and the current injected into the grid accurately follows the reference imposed by the operator. In Fig. 6 are presented the results of the model with variation in the time input power.

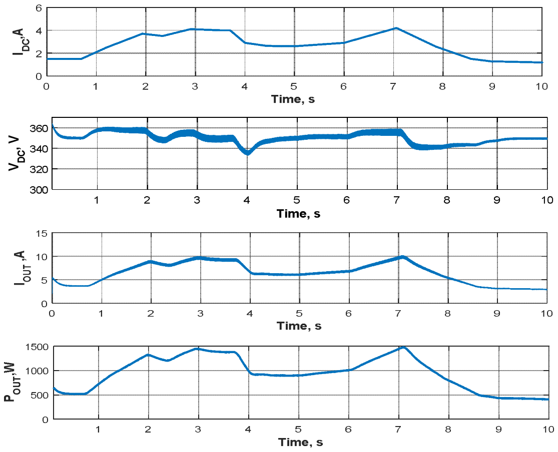


Figure 6. Simulation results: current and voltage of the DC bus, current and power fed into the grid

The input power variation is simulated by variation of the inverter input current – upper curve. The voltage controller calculates the value of the AC current at the inverter output and thus maintains V_{DC} constant. V_{DC} is presented in the second graph. Its changes are within the limits of ±10V, which is ±2,5% from the desired value of 350V. The third graph shows the RMS value of the output current I_{OUT}. The last graph shows the active power supplied to the grid. It is clearly visible that the output current and active power follow the curve of the input current which demonstrates power balance and fluent operation of the controllers.

Fig.7 shows the voltages and currents at the grid side of the inverter. It illustrates the operation of the current controller, PWM and the filter. The output current is in phase with the grid voltage. High-frequency current ripples are very well filtered. However, there are small distortions in the current reference due to the non-constant output voltage of the VDC controller.

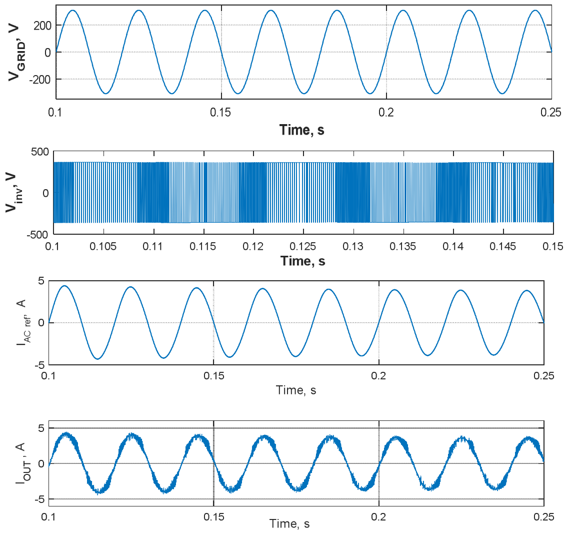


Figure 7. Simulation results: waveforms of the grid voltage, the inverter output voltage, the grid current reference and the inverter output current

II. CONCLUSION

A MATLAB model of the converters and their control system is developed. Simulations are performed with a variable input current reference. The results demonstrate proper operation of the model and its control system. The boost converter control system maintains precisely the given current reference. The grid current and DC-link voltage controller properly follows the reference values. The grid current ripple is not considerable due to the proper sizing of the grid filter. The presented model can be developed further for Hardware in the Loop implementation and the grid current control system can be further developed to control also the reactive power exchanged with the grid.

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