By: **Aaron S. Tint**, (Ph.D.), Senior Design Engineer, Liebert Corporation (North America) and **Ashim Chakravorti**, (Ph.D.), Senior Development Specialist, Liebert Corporation (North America).

UPS System Modelling

Programmable digital signal processors (DSPs) are being used in modern UPS systems. Here are a few models for UPS systems, which use the Matlab/Simulink tool to verify and develop complex algorithms.

Due to the emergence of new technologies in the fields of digital signal processors (DSPs), microcontrollers and power electronic devices, the power systems industry has evolved rapidly within the last decade. Several simulators, with different capabilities, are available and the effect on the technological advancement of simulation tools has taken a giant leap in the modelling of the advanced UPS (uninterruptible power supplies) systems. At the heart of power electronics and UPS industries, lies the family of fast switching devices, the thyristor, the GTO and the IGBT. These devices are controlled to affect the desired power flow to the critical load.

The industry has also taken advantage of the accelerated growth in the speed and memory capacity of the digital controllers. Modern controllers use programmable DSPs that enable the use of intricate control algorithms. In order to verify and develop these sophisticated algorithms, a simulation tool that exhibits a strong interaction between sources, loads, power devices and control circuits is required. Many commercial simulation tools such as Matlab/Simulink, OrCad/Pspice, Simplorer and Saber are available in the market place and each one of them has its own advantages and disadvantages. The differences mainly are the simulation time, user-friendliness or difficulty of use, and the availability of pre-built control elements or blocks such as six pulse rectifiers or inverters. Although the Matlab/Simulink simulation tool has fast simulation time, the execution of the high frequency switching power applications on memory-expanded fast computers still requires large computation time to get to a steady state solution. The design and simulation programs developed at the top level in the Simulink environment can automatically be created into the optimised C/Assembly code that can be downloaded onto the hardware DSP board for real-time execution.

Some basic models for UPS systems are presented here, based on the Matlab/Simulink platform. The closed loop control algorithms for the rectifiers or inverters are tested (iteratively) by mathematical modelling and simulations, to achieve the various design results. Steady state simulation results from the output waveforms, which are analysed in the time domain. The total harmonic distortion (THD) simulation results are compared to experimental results for different load conditions. In addition, the simulation for load transitions is also analysed.

Basic UPS system model

The basic block diagram for a UPS is as shown in Figure 1. The UPS module is usually provided by a bypass circuit that transfers automatically to the normal source if the UPS fails. The battery in a UPS system is typically sized to carry the emergency load for about 20 minutes. The UPS systems

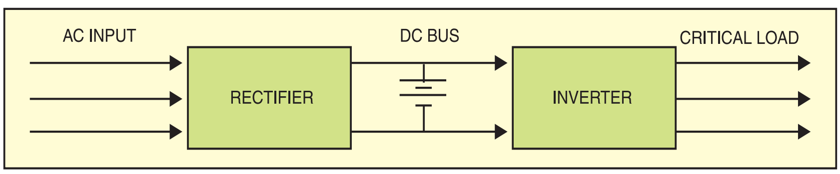

Figure 1: Basic UPS block diagram

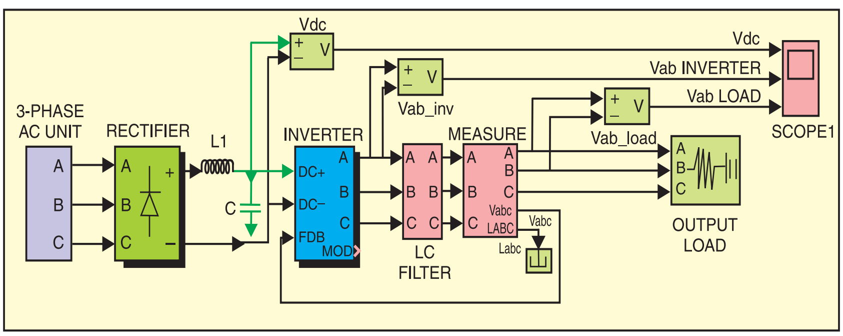

Figure 2: Simulink model of the basic UPS block diagram

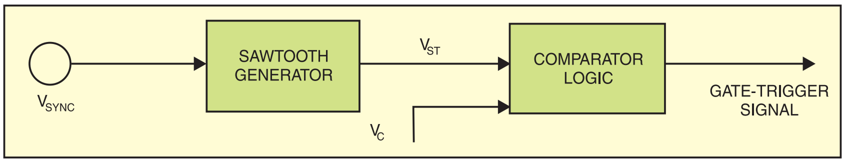

Figure 3: Gate trigger control circuit

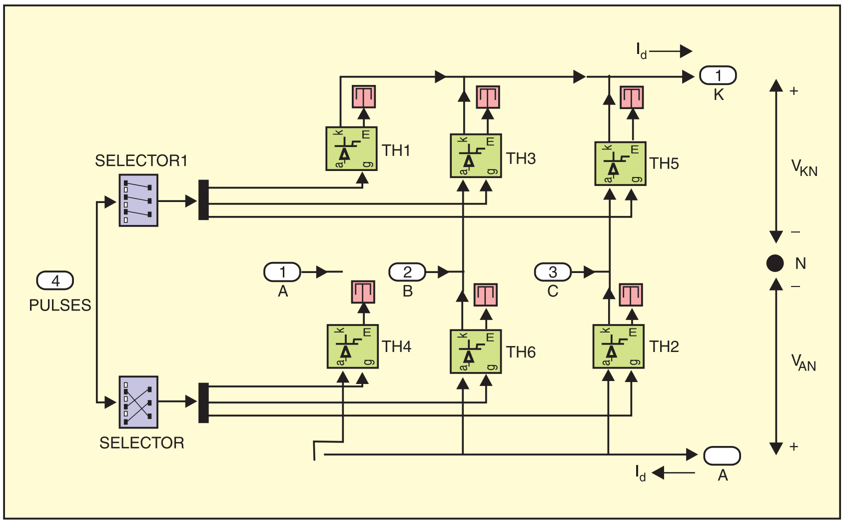

Figure 4: Three-phase six pulse thyristor bridge

are usually designed to provide fast voltage regulation for any level of line voltage. Regardless of power rating, the UPS module includes the three main sections: namely the rectifier section that converts the AC power to DC power, the DC section called DC link or DC Bus, and the inverter section that converts the DC power to AC output power at the desired frequency, voltage and waveform.

The top level Simulink model for the basic UPS block diagram of Figure 1 is shown in Figure 2. Each one of the control blocks, such as the rectifier and inverter, have one or more combinations of lower level of developments that are modelled appropriately to give the desired outcome.

MATLAB is a computing platform for solving circuit equations and developing/testing algorithms. Used in conjunction with the available toolboxes such as the signal processing toolbox, the filter design toolbox and the control toolbox, the algorithms can be analysed and modelled to study the behaviour of power electronic systems prior to prototyping. Simulink is a graphical block diagram hierarchical modelling tool. It provides signal sources like signal generators to stimulate the models and sinks, such as oscilloscopes and spectrum analysers, to visualise the output of the results. In addition, Simulink also provides libraries of pre-built blocks called block sets. The block set includes applications for power systems, digital signal processing, real-time development works and many others. The model shown in Figure 2 uses the power system block set that provides pre-built blocks such as IGBTs and diodes related to power applications.

Rectifier modelling

In most UPS systems, the rectifier or charger performs dual roles. First, it provides the DC power by constant output voltage to the DC bus to feed the critical load either directly or through the inverter. Second, it maintains full charge on the system battery, recharging it after the power outage. To accomplish these requirements, despite variations in the AC line input and the inverter load connected to it, the rectifier/charger is usually designed as a closed-loop controlled circuit. Many types of controls are used, in practice, with different degrees of complexity and performance characteristics. The most common type is the SCR or thyristor phase controlled rectifiers.

The thyristor has an external terminal called gate that controls the conduction current in the forward direction, when the gate voltage is applied. By delaying the gate voltage signal (increasing the firing angle) with respect to the AC voltage applied to the thyristor, the conduction period can be controlled with the subsequent regulation in the DC output voltage of the rectifier.

A simplified block diagram of a gate trigger control circuit is shown in Figure 3. In this figure, a sawtooth waveform (synchronised to the AC input) is compared to the control signal (v_c), and the delay angle á with respect to the positive zero crossing of the AC line voltage is obtained in terms of v_c and the peak value of the sawtooth waveform v_{st}. This is given as:

v_c (degrees) = 180*(v_c /vst)

The three-phase six-pulse bridge rectifier is very widely used. The bridge is supplied with the three phase input signals. A smoothing filter capacitor is normally connected at the DC output of the rectifier. In Figure 4, the thyristor (or diode) in the top group, with its anode at the highest potential, will conduct and the other two become reverse-biased. In the bottom group, the thyristor with its cathode at the lowest potential will conduct and the other two become reverse-biased.

The instantaneous voltage (v_d) consists of six segments per cycle of the line frequency, and each thyristor in the bridge conducts for 120 degrees (maximum). The voltage and current waveforms may be represented mathematically for the analysis of the rectifier model. The basic equations for phase A are given as follows:

$v_d = v_{Kn} - v_{An}$ and
$I_a = I_d$ when th1 is conducting;
$= -I_d$ when th4 is conducting;
$= 0$ when neither th1 nor th4 is conducting

The average DC output voltage and rms of the line currents may be computed for each of the six segments.

By controlling the instant at which the thyristor gate is turned on, the average forward current and, therefore, the voltage can be controlled in a continuous manner between the desired DC bus voltages.

A proportional-integral controller is usually incorporated in the rectifier block to improve the response of the regulation system.

Inverter modelling

In the UPS system, the design for the inverter is most critical since it determines the quality of the power delivered to the load. The inverter takes its power from the DC bus (rectifier or DC source) and converts it in a manner usable for the critical load. The critical load expects a sinusoidal AC voltage source. The inverter produces a voltage source that has harmonic voltages in addition to the fundamental frequency. The deviation of the inverter output voltage from a true sine wave can be measured as total harmonic distortion (THD). The THD is mathematically defined as the root mean square (RMS) value of the total harmonics of the signal, divided by the RMS value of its fundamental signal. The THD of the measured current is defined as:

Total harmonic distortion (THD)$=I_H/I_F$

where $I_H = \sqrt{I_2^2 + I_3^2 + \ldots\ldots + I_n^2}$

I_n is the RMS value of the harmonic n

I_F is the RMS value of the fundamental current.

The basic UPS model shown in Figure 2 includes an output AC filter and the load. An output AC filter (inductor-capacitor) is required to reduce this distortion to a lower acceptable level. The use of high-frequency switching using pulse width modulation (PWM) provides improved transient performances with reduced AC filter size.

Table 1: System Parameters for Inverter Simulation

DC bus voltage	Vdc	540V (norm), 390V(min)
AC output voltage	Vload	208V (LL-RMS), 120V(LN)
Frequency	f	60Hz
Inverter filters	C_{inv}	900 μF
	L_{inv}	184 μH
Delta-Wye transformer	L_{trans}	43 μH
	R_{inv}	0.0162 ohm
Output filter	C_{hf}	90 μF

This type of modulation has been very popular and is widely used. As fast DSPs and microcomputers become available, the technique based on the pre-programmed PWM pattern have also been used. More recent techniques include the time optimal response switching PWM and the real-time deadbeat controlled PWM. These techniques have very fast responses, but are also known to have high THD for non-linear loads. The techniques developed at Emerson Network Power use algorithms for perfect tracking of the output voltages under unknown load by eliminating errors at certain specific harmonics and at the same time ensuring good transient response.

The control system involves the fast inner current loop for limiting the inverter currents, under overload conditions and the outer voltage loop to control the voltage harmonics. The outer voltage loop is designed by accounting for the extra dynamics introduced by the inner loop. It has been generally reported that space vector modulation techniques provide superior performance compared to regular PWM, in terms of reduced harmonic current ripple, optimised switching sequences and THD. Multi-dimensional state space model representations are used for the computation of the gain parameters of the controllers. The plant is modelled by the following basic state space equations:

$x = Ax + Bu + Ed$
$y = Cx + Du + Fd$
$y_m = C_m x + D_m u + F_m d$
and the error signal $e = y_{ref} - y$

where x and u are the inputs, y is the output to be regulated, y_m are the measurable outputs, d is the disturbance and y_{ref} is the reference input signal. The parameters (A, B, C, D, E, F) are the matrices of several orders that represent the plant (LC filter, .-Y transformer, Grass capacitor and Load). The multi-dimensional gain values are evaluated using different criteria to provide optimal values.

The inverter simulation is performed by using the system parameters as shown in Table 2.

The simulation is carried out for various linear loads, 0.8 power factor loads, no loads, unbalanced loads, and crest factor loads.

The above sections prove that critical operation of the UPS system can be adequately modelled to look into various steadystate and transient modes of operation. The simulation model can therefore be extensively used to understand the details of power flow phenomenon between various modules and within various devices. The knowledge from the simulation results provides valuable insight into design/performance constraints and failure mode analysis.

Results

The THD measurements for different load conditions are summarised in Table 2. The load current of 2.7:1 crest factor is used for the non-linear load. The results are compared with the experimental values obtained from the hardware test measurements. The results can be improved by including more harmonics to be eliminated into the derivation of the robust voltage controller. The simulation tests for the load transients, 0 to 100 per cent and 100 to 0 per cent, also show that the load voltages recover within less than a cycle of the waveform. The deviations of the magnitudes of the output voltages are less than 5 per cent of the nominal values. The results also show that the closed loop controls provide fast response with less overshoots.

DSP controls firmware developments

The design and simulation of the control algorithmic model developed on Matlab/Simulink uses several floating-point calculations with very high sampling rates. The DSP block set and the Real Time Workshop platform provide the necessary transformations and links to the embedded target digital signal processors. The design algorithms are generally written in the form of assembly or C codes and the (assembled and linked) executable codes are downloaded to the target processors for firmware testing. The Matlab/Simulink platform provides a

Table 2: Output THD for Different Types of Loads

Load	THD
Linear resistive full load, 1.0PF	0.8%
0.8 power factor load	1.01%
No load	1.1%
Unbalanced resistive load (Phase A)	0.92%
Crest factor load (2.7:1)	4.9%

real-time data exchange (RTDX) port that allows hardware DSPs to read and write data (back and forth) in real-time. By using the RTDX bi-directional link, the calculation-intensive control algorithms (optimised codes automatically generated by the Real Time Workshop—or hand-coded assembly program—and subsequently compiled, linked and downloaded to the DSP) are computed in real-time and the resulting data are imported back into the Matlab/Simulink environment for analysis and display. This DSP-in-the-loop set-up gives a way to create some really reliable code with fewer errors. The procedure is used for the earlier generation TI320C234 signal processors. For the later generation DSPs, such as TI C6000 processors, Matlab/Simulink offers two integrated verification and debugging tools. These are:

- The Embedded Target for C6000 DSP Platform and
- The Matlab link for assembler/compiler, linker environment (Code Composer Studio Development Tools).

The Embedded Target for C6000 DSP Platform enables the rapid prototyping of real-time software for Texas Instruments (TI) C67x floating-point and C62x fixed-point DSPs. MATLAB Link for Code Composer Studio Development Tools provides a bi-directional interface between MATLAB and Code Composer Studio, the Texas Instruments software development environment.

Some basic building blocks/models for UPS systems have been discussed here, based on the Matlab/Simulink platform. The closed loop control algorithms for the rectifiers or inverters are tested for different load conditions and the transients. The comparison of THD for simulation and experimental data shows that the results are in close range. Various approaches at different stages in the design process can be tried to achieve stable and safe operations, and this is especially important for UPS applications involving high KVA ratings.

The simulation models for the UPS provide important technical information about the behaviour of the system within a shorter period of time. The rectifier, inverter, voltage and current controllers are developed in the form of modules and the interactions between different modules are analysed, using various design criteria. The performances had been evaluated for different design constraints and the simulation results meet the design specifications. The oscilloscope time signals or the fast Fourier transform (FFT) frequency spectrum can be inserted at several strategic points to determine signal waveform characteristics or the harmonics. The design can be altered at minimum cost with fast reliable results.