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Simulation Based Design for Inverter Power Supply

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Inverter power supplies have been developed as an analog circuit. Over the past decade, digital control has emerged as a viable candidate for the inverter power supplies due to the benefits which can be added by applying the digital control. However the complexity of digital control has been dramatically increasing. One of the leading methods in the digital control design is the model based development technique. Modeling and simulation act as the first step of model based development technique and they are very useful for the development and implementation in both hardware and software. They can lead to improve the performance, reduce development and production cost and time. This paper constructs a Model In the Loop Simulation (MILS) environment for designing the embedded software for the inverter power supply. The principle of the operation and the key features of using the digital PWM controllers are presented. Moreover, the important software parameters are optimized using the simulator. To verify the validity of the developed model, comparisons between the circuit simulation and experimental results are shown. The illustrations show that the results obtained by the developed model are in good agreement with the experimental results.

1. Introduction

Inverter power supplies are widely used in many industrial processes and applications, such as, uninterruptable power supplies, motor control, and electric vehicle applications. An inverter power supply can be defined as a device that converts DC (Direct Current) from sources such as batteries, solar panels, fuel cells, or wind generations to AC (Alternative Current) so that the output can be used in a wide range of AC applications. Traditionally, an analog control technique is used to control the inverter power supply. However, due to the fact that a digital control technique can provide the benefits which can not be provided by an analog one, a digital control starts to be used. Actually, a digital controller can offer a programmable solution for the applications. Moreover, it also offers the flexibility in design and an advanced algorithm and additional features can be added to the controlling software instead of hardware.

From the electrical view point, a digital controller is less sensitive to the environmental conditions and shows precise behaviors compared to analog counterparts [1)–4)]. However, the complexity of digital control in many applications has been dramatically increasing over the past few years. It is becoming difficult to monitor the control behavior for the actual design. In the digital control, the system can be classified as an embedded system which consists of two parts, the first part is the control part which includes the microprocessor or DSP and the control software (embedded software), the second part is the controlled part which could be electrical or mechanical part. Within the scope of our investigation, all the previous study concentrated on the modeling of the analog part and the digital pulse was generated by pulse generator [3),5),6)].

So in the actual implementation, the software needed to be tested in the actual prototype which may lead to system failure as well as it takes so much time to obtain the optimum parameters. On the other hand, there are some studies dealing with the digital part as an actual implementation [7),8)] or comparing theoretical and experimental aspects of inverter power supply design [9)]. Due to the previous work in the inverter power supply design, there are many challenges which open a wide range of research fields. Some of these challenges include the difficulty to monitor the control behavior before the actual implementation, time needed to optimize the software parameter, verification of the control algorithm and the time to market. One of the leading solutions of this problem is to apply model based development technique.

In this method the model can be used to verify the plant design and the control algorithm. This paper describes how the model based design can offer an effective solution in the inverter power supply design. The main goal of this research is to propose full system simulation including both the analog and digital parts by constructing Model In the Loop Simulation (MILS) environment to overcome some of the previous challenges. In this research, the function of both the analog

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part and the digital part is tested in the model environment. This method can lead to many advantages, it can provide insight into the system performance and allow for analysis of the design before it is implemented in the hardware and software, which can lead to improve the performance and to reduce the time and cost. Moreover, it will reduce the time needed to optimize the software parameters and it gives the designer the ability to add some new features in the software to improve the system performance.

This paper is organized as follows. Section 2 includes the description of the inverter power supply topology. A single phase pulse width modulation is presented in Section 3. Section 4 presents the description of the MATLAB model of the inverter power supply and comparisons between the simulation and the experimental results are described in Section 5.

2. Description of Inverter Power Supply

Aforementioned, an inverter power supply is a device which can convert DC to AC that can be used in various AC applications. It can be classified into two main groups, single stage inverters and multi stage inverters. Each group has different topologies, multi stage inverters will be described in this section. A multi stage inverter is defined as an inverter with more than one stage power conversion. There are many different topologies, which are used to determine the parts of the inverter power supply, listed below [10]:

1) DC-DC-AC topology,
2) DC-AC-DC-AC topology, and
3) DC-AC-AC topology.

The choice of such topology depends on many factors, such as, size, cost, efficiency and capability. In this paper, DC-DC-AC topology will be used; and its configuration is broken into two stages. The first stage is to step up the DC voltage level by using a DC/DC converter and the second stage is to invert DC to AC through a DC/AC inverter. Each stage can be controlled individually or synchronously. An SH microprocessor will be used to control the operation of both stages individually. The block diagram of the inverter power supply is shown in **Fig. 1**.

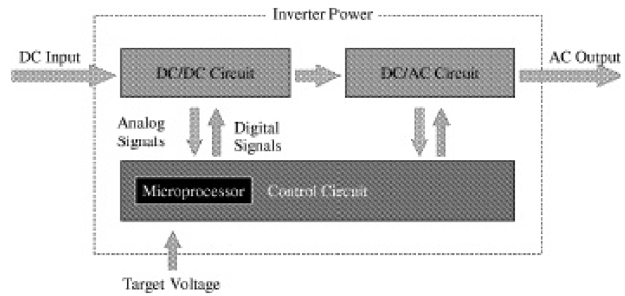


Fig. 1 Block diagram of inverter power supply.

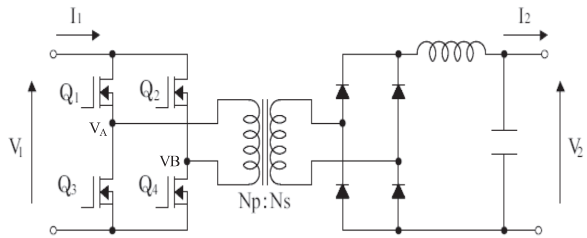


Fig. 2 Circuit schematic of DC/DC converter.

2.1 DC/DC Converter

As shown in Fig. 1, the first step of the inverter power supply is to step up the DC voltage level to the higher DC voltage level by using a DC/DC converter. One of the simplest and most cost-effective configurations of DC/DC converter is the full bridge configuration shown in **Fig. 2**. This type of converter operates by varying the pulse width at the switch gates of the transistors, which varies the average voltage at the mid point (V_A, V_B) of each leg by using the Pulse Width Modulation (PWM) technique. The output voltage taken across the midpoints is applied to the transformer which is responsible for boosting the voltage level V_1 to the higher voltage level V_2.

2.2 DC/AC Inverter

The second stage of the inverter power supply is to invert the new DC voltage into AC voltage through a DC/AC inverter. The most common topology is a full bridge configuration because of its easy filtering [8),11)]. A single phase full

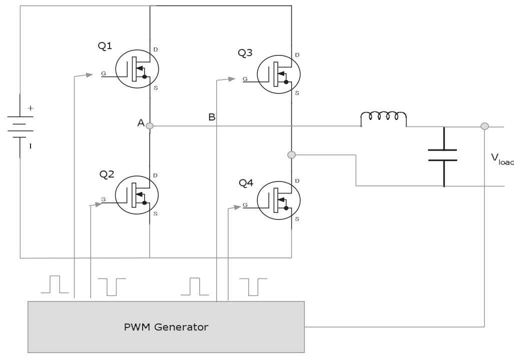


Fig. 3 Circuit schematic of DC/AC inverter.

bridge inverter is shown in **Fig. 3**. The PWM pulses which are generated by a microprocessor are fed into the gates of the full bridge inverter. Programming a microprocessor allows the transistors Q_1 and Q_4 to be on while Q_2 and Q_3 to be off and vice versa.

A protection is implemented by providing a short time delay between the turning off of switching device to the turning on of the other switching device in the same leg to prevent shorting of the DC bus (current short through) which is called "dead time" [2]. The shorter is the dead time, the better is the inverter performance. It is usually between 1 and 5 μs. The details about the PWM pulse generation and microprocessor programming will be mentioned in Section 3.

2.3 SH Microprocessor

In the inverter power supply applications, the microprocessor is used to control the switching period of the transistors as a digital controller. However, due to the fact that a digital PWM technique can provide the benefits which can not be provided by an analog one, a digital PWM technique starts to be used [7),12)]. The standard method for generating PWM pulses by using a microprocessor or DSP is by using one of the built-in PWM modules. These modules operate by comparing a free running timer with a duty cycle and duty period register. When a matching occurs between the timer and duty cycle register, the corresponding pin is either set to "high" or "low". The matching between the timer and the duty cycle register also causes the timer to reset to zero and then, to restart

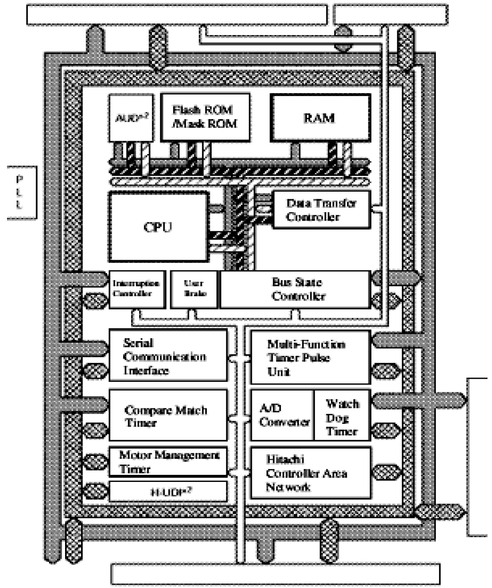


Fig. 4 Block diagram of SH microprocessor.

counting [2),12)]. Depending on the type of microprocessor or DSP, the PWM can be classified into "left-aligned", "center-aligned" or "right-aligned". To improve the performances of the digital PWM pulses, a digital control technique should be used. The digital PI (Proportional and Integral) controller is used to control the generation of PWM pulses. The main reason to use the PI controller is its simplicity and flexibility [12)]. In this paper, a Renesas SH-2 microprocessor is used to control the generation of the PWM pulses which control the operation of both DC/DC and DC/AC circuits. The block diagram of the microprocessor is shown in **Fig. 4**.

In the SH-2 Microprocessor, there are two separate control units which are Motor Management Unit (MMT) which controls the generation of the PWM pulses in the DC/DC stage and Multi-function Timer pulse Unit (MTU) which controls the generation of the PWM in the DC/AC stage [13)]. The generation of the PWM waveforms is a part of the software solution and this software is known as embedded software. Embedded software that is implemented in the microprocessor can be divided into three main tasks which are the wave generation task, the task based on a control algorithm and the man-machine interface task.

3. Pulse Width Modulation

Nowadays, Pulse Width Modulation (PWM) plays a major role in the generation of pure sine waves[3]. PWM can be defined as a switching method which is used for the inversion of DC to AC, where the pulse width (duty cycle) at the switching gates of the transistors varies according to a sinusoidal reference signal (control signal). Generation of PWM patterns can be done by using two different techniques which are analog or digital techniques[10),14]. For understanding the methodology of PWM, an analog PWM is described below. The PWM can be done simply by comparing a sinusoidal control signal at the desired frequency with a triangular waveform (carrier signal). At each point, where the control signal and the carrier signal intersect, the output of PWM toggles from a high state to a low state as shown in **Fig. 5**.

The frequency of the carrier signal is generally kept constant along with its values. The control signal is used to control the switching duty by changing its values as a factor called modulation ratio "m" as described in Eq. (1).

$$m = V_{controller}/V_{carrier} \quad (1)$$

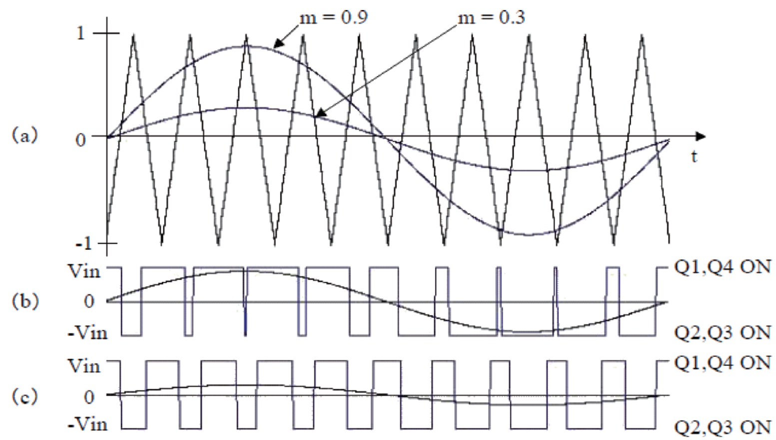


Fig. 5 PWM pulse generation.

Where, $V_{controller}$ is the peak amplitude of reference sine wave and $V_{carrier}$ is the peak amplitude of saw-tooth wave, respectively. In this paper, digital PWM technique is used by utilizing SH microprocessor to control the generation of PWM pulses as described in Section 2.

4. Description of MATLAB and Simulink Model

Due to the complexity of the digital control design, the model based development technique is considered one of the leading solutions. In this method, modeling and simulation are considered as vital parts of design. Particularly, the simulation is indispensable for developing a controller programs. It can lead to the performance improvement and the reduction of the cost and the time for development and production. There is variety of software tools that are used for that purpose including MATLAB and Simulink. MATLAB and Simulink are software tools designed for modeling, simulating and analyzing the design of This supports linear and nonlinear system models in continuous time, sampled time or combination of both It consists of a set of blocks such as communications, controllers, power systems and neural networks, etc. There are a lot of available tools that can be used in the MATLAB environment to design and optimize the performances in an effective and easy way[11]. In our approach the entire inverter power supply system will be modeled by constructing a Model In the Loop Simulation (MILS) environment. The MILS environment is divided into two main parts, the analog part and the digital part which are described as follows:

Analog part consists of DC/DC converter and DC/AC inverter electric circuits. Both of these circuits are modeled using the Simulink power block set which consists of power electronic devices and elements such as inductance, capacitance and resistance, as shown in the upper part of Fig. 7. The second part, which is the digital part or the controller part, is responsible for the digital pulse generation which controls the analog part. This part consists of the SH microprocessor and the embedded software. The digital part is modeled by simulating the function of microprocessor or the embedded software function. As mentioned in Section 2.3, the inverter power supply stages are controlled individually using the SH microprocessor which has two controlling units. The first unit is Motor Management Timer (MMT) which controls the operation of the DC/DC converter stage and

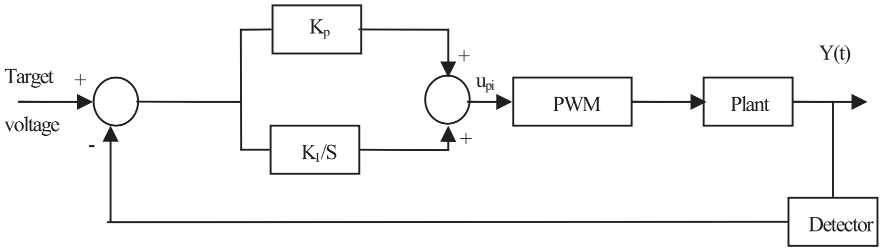


Fig. 6 Classical PI controller.

the second unit is Multi function Timer Unit (MTU) which controls the operation of the DC/AC inverter stage. Each microprocessor unit has two main tasks, that is, the controlling task executing the Proportional-Integral (PI) controlling algorithm and the PWM generation. The description of these two task models are as follows.

4.1 Controller Algorithm

The main purpose of using the PI controller is to control the generation of the PWM patterns. This is used to control the operation of both of the stages to produce the sinusoidal output voltage with a low total harmonic distortion. Among the digital controller techniques, the digital PI controller has been used in many industrial applications. The main reason for using the PI controller is its simple structure which can be easily understood and implemented in the practical usage as well as its flexibility.

The following equation describes the PI controller algorithm.

$$u_{pi} = K_p e(k) + K_I \sum_{n=1}^{k} e(n)$$

where K_p and K_I are the proportional and the integral coefficient, respectively, $e(k)$ is the error signal, and u_{pi} is the controller output. **Figure 6** shows the block diagram description of the PI controller algorithm, the output of the PI controller algorithm u_{pi} controls the PWM generation stage which generates the pulses to control the operation of both of the DC/DC and DC/AC electric circuits. The values of the proportional coefficient and the integral coefficient are optimized based on the trail and error technique to obtain the required output.

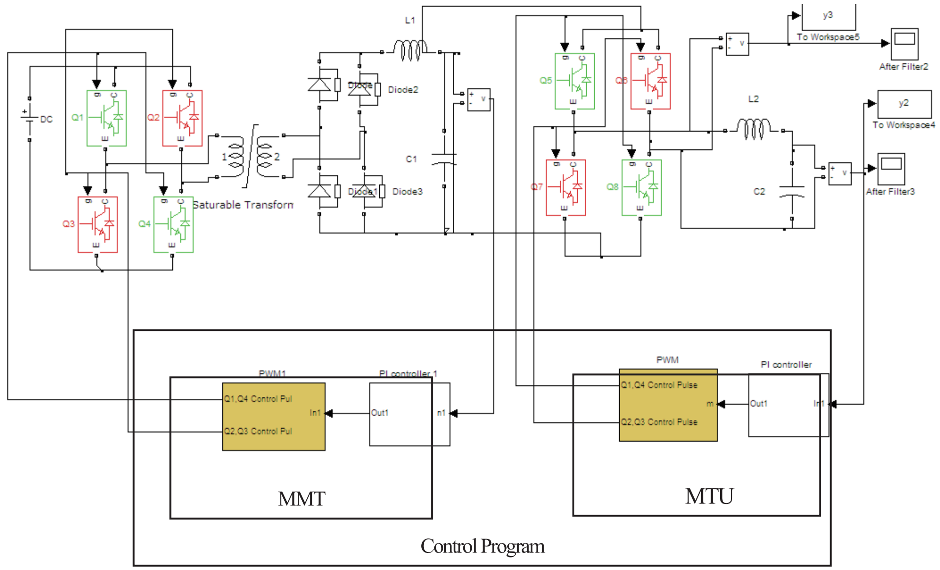


Fig. 7 MATLAB model of inverter power supply.

4.2 PWM Generation Program

The standard method for generating PWM pulses by using a microprocessor or DSP is to utilize one of the built-in PWM modules. In our model, an S-function block is used to compile the embedded programs which control the operation of DC/DC and DC/AC circuits. The S-function can be defined as a computer language description of the Simulink block written in, MATLAB, C, C++, Ada or FORTRAN [11]. We compile two C programs which describe the microprocessor units, MMT and MTU. As shown in the lower part of **Fig. 7**, there are two S-function blocks with two C programs compiled to model the PWM task of the microprocessor units.

5. Experimental Results

The validity and usefulness of the MILS environment construction is verified by comparing its results with the experimental results in the actual device. As shown in **Fig. 8**, actual prototype of an inverter power supply has been fabricated

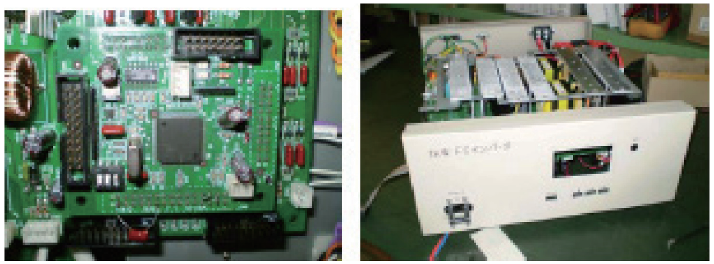
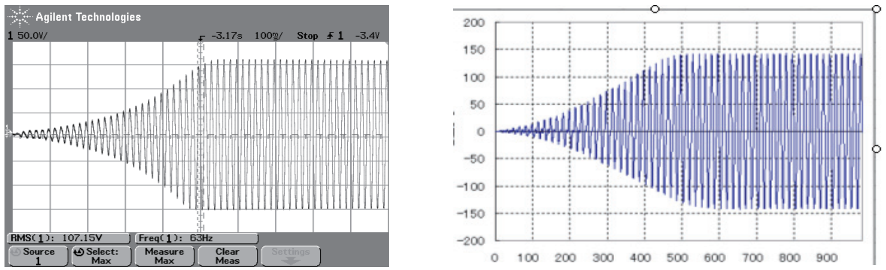
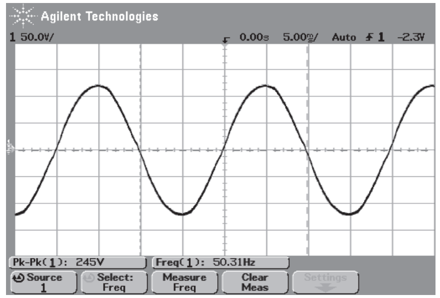


Fig. 8 Actual inverter power supply device.

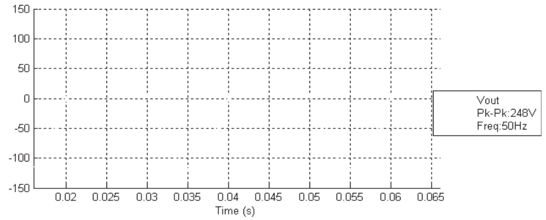


(a) Actual AC Output (b) Simulated AC Output

Fig. 9 Comparison of AC outputs.



(a) Actual Sin Wave Output



(b) Simulated Sin Wave Output

Fig. 10 Comparison of sin wave outputs.

using Renesas SH microprocessor and the embedded program is implemented manually. The input DC voltage is 24 V and the target AC output is 100 RMSV with frequency of 50 Hz.

5.1 Comparison of Output AC

The parameter values which are optimized in the developed simulator are almost the same as those in the embedded program of the actual inverter power supply. Here, the parameters include the PI coefficients, the value of modulation ratio, the dead time value and the device parameters of circuits. This fact shows that the embedded program and the hardware developed heuristically is almost optimal.

Figure 9 (a) shows the AC output of the actual prototype and Fig. 9 (b) shows the simulated AC output of the developed simulator. By comparing the results in both figures, it can be seen that the shapes of the waveforms are almost identical. The actual device reaches the desired stationary voltage after 550 ms while the MILS model reaches the stationary AC voltage at 522 ms it means the simulation time in less than the actual time by about 5.4% So, we can conclude that the developed models can simulate the actual prototype in a good way in very short time.

5.2 Pure Sine Wave Output Voltage and Frequency

Figure 10 (a) and (b) shows the actual sin wave output and the simulated sin wave output respectively. Comparing the two waveforms, it can be seen that the result obtained by the developed simulator is in a good agreement with the actual results for both of the frequency and the voltage values. The efficiency of the model can be calculated be comparing the simulated peak voltage and the actual peak voltage. The efficiency of the proposed model is 99%. We can conclude that the developed model can accurately model the actual prototype.

It is shown from the above results that the accuracy of the simulation results is very high, it reaches 99% as well as the speed of the MATLAB simulation is fast comparing with the other simulation program, generally, MATLAB/Simulink approach is hundred times faster than PSPICE approach [6),10)]. The usefulness of the proposed method can be observed by comparing it with the traditional inverter power supply design. Traditionally, in the inverter power supply design, the software is always tested by using the actual prototype and this may lead to system failure as well as it takes so much time to optimize the software parameters. Therefore, the time for improving the software is limited and it will be difficult to add some new features in the system. By applying the MILS environment, we may solve some of these challenges, so the MILS environment helps to optimize the software parameters and to validate the control algorithm in short time and with low cost. As well as applying the MILS in the early design stage, it can contribute to the reduction of system development period and guarantee the robustness of the system design.

6. Conclusion and Future Work

This paper presents Model In the Loop Simulation (MILS) of the inverter power supply as the first step of applying the model based development technique using the MATLAB and Simulink environment. The validity of the suggested models is tested by comparing them with the actual inverter power supply prototype. The developed model was shown to be well in agreement with the experimental results. The accuracy of the proposed model reached 99%. Therefore, the MILS environment can be used to optimize the software parameters before the actual design. Moreover, it can be used to study and analyze the behaviors of the system which meet the challenges of designing the digital control system. As well as applying the MILS in the early design stage, we can contribute to the system development period reduction and guarantees of robust system design. As a future work, the accuracy of the proposed simulator must be improved and some modifications will be added to the MILS to tune the circuit parameters as well as software parameters automatically.

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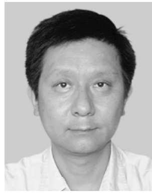

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