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Modeling of Power Electronic Systems with EMTP

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MODELING OF POWER ELECTRONIC SYSTEMS WITH EMTP

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ABSTRACT

In view of the potential impact of power electronics on power systems, there is need for a computer modeling/analysis tool to perform simulation studies on power systems with power electronic components as well as to educate engineering students about such systems. This paper describes the successful modeling of the major power electronic components of the NASA Space Station Freedom Electric Power System, EPS, with EMTP (ElectroMagnetic Transients Program) and demonstrates that EMTP can serve as a very useful tool for teaching, design, analysis, and research in the area of power systems with power electronic components. The paper describes EMTP modeling of power electronic circuits and presents simulation results.

1. INTRODUCTION

With the advent of semiconductor technology, power electronic circuits and systems will play an increasingly significant role in electric power systems. Power electronic systems such as high voltage direct current (HVDC) transmission systems and static var compensation (SVC) systems have already been installed in some power systems to enhance electric power transmission and to improve the overall system performance Other examples include power conditioning units that connect alternative energy sources (e.g., photovoltaic and wind energy) to utility power systems, motor drive systems for industrial applications, utility interconnection to energy storage systems (e.g., battery, fuel cells, superconducting magnetic energy storage), etc. Besides improvement and innovative uses of existing devices and systems, there are many opportunities for developing new devices, systems and applications.

In view of the potential impact of power electronics on power systems, there is need for a computer modeling/analysis tool to perform simulation studies of power systems with power electronic components. Such a simulation tool could be used to study the operation of individual subsystems and their interactions, to investigate various system operation and design concepts, to analyze and compare different control and protection strategies, to examine the impact of undesirable effects such as harmonic distortions, to investigate potential problems such as resonance, etc.

The National Aeronautics and Space Administration (NASA) is undertaking the development of Space Station Freedom, a manned base that would remain in low earth orbit for an indefinite length of time, for scientific, technological, and commercial purposes. NASA Lewis Research Center is responsible for the design, development and fabrication of the Space Station Electric Power System (EPS). Among the technologies under investigation is a 20 kHz single phase, 440V, power management and distribution (PMAD) system . The PMAD system is designed to convert power from the solar-based energy sources (photovoltaic/solar dynamic) to 20 kHz for transmission and to distribute it to various types of customer loads, both dc and variable frequency ac. The initial system capacity is 75 kW. The system is planned to grow up to 300 kW in subsequent phases. Although operated at a much higher frequency, the EPS resembles a terrestrial utility power system (60 Hz) in many respects.

NASA Lewis Research Center has built a power system facility for testing the hardware and software to be developed for the EPS. Modeling capability for simulation studies is also under development A preliminary study has been performed to investigate the feasibility and appropriateness of using EMTP (ElectroMagnetics Transients Program) [1] for the modeling of EPS with special emphasis on power electronic devices. Results of this study are described in this paper.

The objective of this paper is to demonstrate that EMTP can be used as a tool to model power electronic components (including high frequency operation) and their interactions with the power system. Engineers can use EMTP for simulation of power electronic systems while educators can also use it as a teaching tool for such systems. New challenges associated with power electronics and new applications such as space power systems could stimulate more interests among students to study power systems.

A brief overview of EMTP is provided in Section 2. The modeling of major power electronic components in the EPS is described in Section 3. Applications of EMTP are discussed in Section 4. Conclusions are presented in Section 5.

2. BRIEF OVERVIEW OF EMTP

EMTP is a well-known network simulation software tool for power system simulation studies, used extensively by utility engineers. Presently, versions of EMTP are available for a variety of computers including personal computers [2,3]. EMTP continues to be updated with new features as need arises.

The theoretical basis of EMTP modeling is explained in [1]. To model a power system, an EMTP user assigns a name to each node of the network and specifies how the nodes are connected. Models of a variety of power system components are available in

EMTP. Alternatively, the user may set up a model of his own device.

Control systems are modeled by using the TACS (Transient Analysis of Control Systems) program of EMTP. During each time step, voltage, current, or other data measured from the power system are used by the control system to determine appropriate control actions (e.g., turning switches on/off), which are, then, fed back to the power system for execution. Interaction between the power system and its control system can be simulated accurately.

Initially, TACS was developed to model the HVDC converter control system and the resulting simulation results were validated against field data [4]. EMTP has also been used to simulate the operation of static var compensators. However, modeling of other power electronic circuits using EMTP is not widely reported. The modeling of two power electronic circuits, which are being considered for the EPS, is presented in this paper. One of the circuits is a phase-angle-controlled (PAC) resonant inverter that uses thyristors and the other is a pulse-width-modulated (PWM) resonant inverter that uses transistors. Because of the increasing popularity of resonant-mode power supplies [5], these results have future applications. Also, the same modeling technique can be applied to other types of power electronic circuits.

3. MODELING OF EPS POWER ELECTRONIC COMPONENTS

Although the configuration of the EPS is not yet final, NASA Lewis Research Center has assembled a power management and distribution (PMAD) system hardware test bed to support the design and development of EPS where system design issues such as system protection, control, and load management will be addressed. A simplified schematic diagram of the PMAD test bed is shown in Figure 1.DC power from the photovoltaic arrays is converted to 20 kHz ac by the main inverter unit (MIU), which is connected to bus 1 of a 4-bus, 4-line power system. The 20 kHz transmission cable, designed to have low inductance, consists of flat foil conductors with dielectric coating. Line data for this system are given in Table 1.

Line	Resistance (ohm)	Inductance (mH)	Capacitance (μF)
L1	0.0305	0.000171	0.05016
L2	0.0230	0.000129	0.03784
L3	0.0203	0.000114	0.03344
L4	0.0728	0.000408	0.11968

Table 1. Line Data for the 20 kHz PMAD test bed

Because these lines are short (less than 150 feet), NASA studies indicate that a single π-model is sufficient for line representation for most of the simulation studies.

A major component of the PMAD system is the MIU. Two candidate circuits are currently being considered for the MIU. The first is a PAC circuit being developed by General Dynamics while the second is a PWM circuit being developed by TRW.

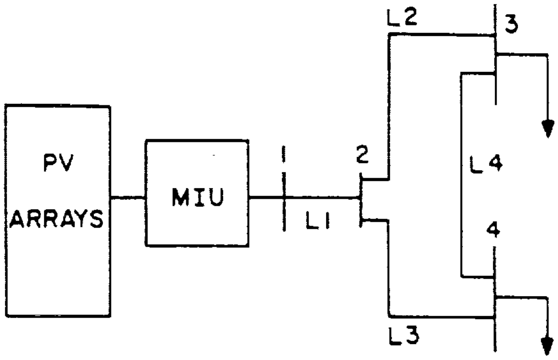

Figure 1. A simplified schematic diagram of the PMAD test bed

A. Phase-angle-controlled (PAC) MIU

The basic component of this MIU is a dc/ac resonant inverter. Figure 2 shows the schematic diagram of this inverter, known as the Mapham inverter [6], wherein the basic resonant circuit is formed by the inductors (L) and the capacitor (C). However, the connected load across the capacitor also affects the resonant circuit. The resonance frequency, *fr*, is determined by the values of L, C, and the load. The operating frequency, *fo*, of the output voltage across C is determined by the gate firing frequency of the thyristors, provided that the ratio, *fr*/*fo*, is greater than unity. This ratio influences the performance of the circuit in terms of efficiency, harmonic distortion, and voltage regulation and is an important design parameter.

The steady-state operation of this circuit is described as follows:

Mode 1 :	Thyristors Q1 and Q2 are turned on and establish a resonant circuit ; current flows from the dc source to the capacitor through Q1 and Q2 and charges the capacitor in the positive direction; currents in diodes D3 and D4 decrease to zero.
Mode 2 :	At the end of half of the resonance period, current reverses direction and flows from the capacitor to the dc source through diodes D1 and D2 ; thyristors Q1 and Q2 are turned off.
Mode 3 :	Thyristors Q3 and Q4 are turned on and establish a resonant circuit ; current flows from the dc source to the capacitor through Q3 and Q4 and charges the capacitor in the negative direction ; currents in diodes D1 and D2 decrease to zero.
Mode 4 :	At the end of half of the resonance period, current reverses direction and flows from the capacitor to the dc source through diodes D3 and D4 ; thyristors Q3 and Q4 are turned off.

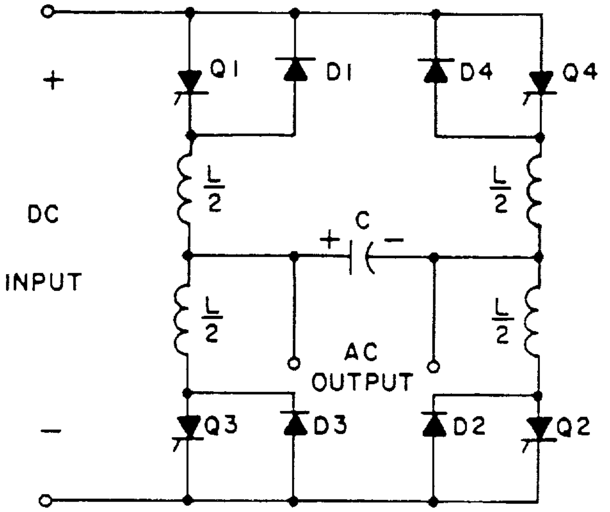

Figure 2. Mapham Inverter

The operation of the Mapham inverter was simulated with EMTP and the results are shown in Figure 3. These results are consistent with those obtained experimentally. For this study, the operating frequency was 20 kHz and the ratio, *fr/fo,* is about 1.4. The electric network portion of this circuit was modeled with existing EMTP features. EMTP also offers models for thyristors and diodes while switch characteristics such as holding current, ignition voltage, and deionization time can be specified. Snubber circuits were also included in the simulation. The gate firing pulses for the thyristors were generated using TACS.

Figure 4 shows the firing pulse generation circuit implemented with TACS. The type-24 device is a signal source generating a periodic sawtooth waveform. Like the other TACS devices, this device is uniquely identified by the name of its output, VSIG.1, as defined by the user. VSIG.1 is the driving signal for a type-51 device, a relay-operated switch. The type-51 device is normally open and its output, TRIG.1 is zero. When the driving signal VSIG.1 is greater than or equal to a user-controlled threshold, VREF.1, TRIG.1 changes to unity.

TRIG.1 is fed to a pulse shaping circuit. DTRI.1, output of the type-53 (transport delay) device, differs from its input TRIG.1 by a user-controlled time delay PULWID. By subtracting DTRI.1 from TRIG.1 a pulse with a controlled width can be obtained. FPULSE is the firing pulse that controls the operation of a thyristor. Since SCRs respond only to positive gate signals, the negative portion of FPULSE does not affect the operation of the circuit and, if desired, may be filtered away by passing FPULSE through a limiter with the lower limit set at zero.

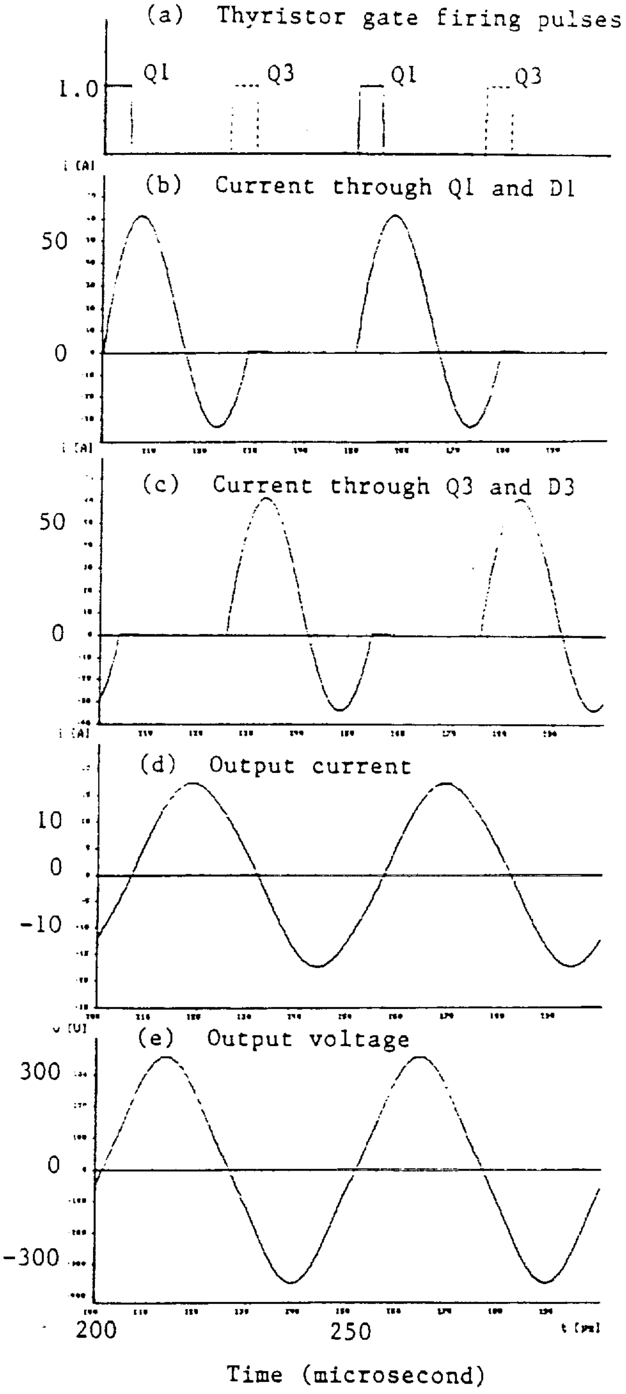

Figure 3. Steady State operation of the Mapham Inverter

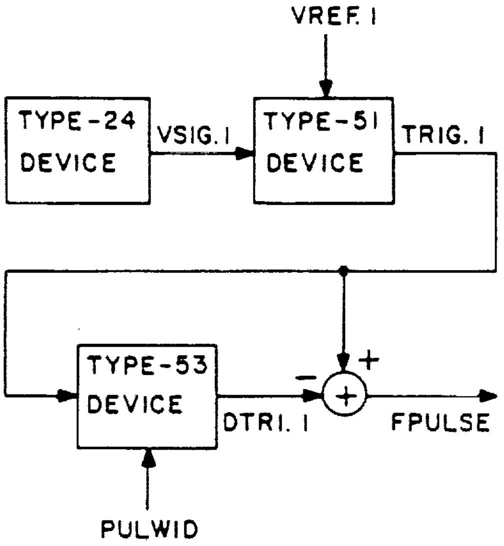

Figure 4. Firing Pulse Generation Circuit

By fixing the period of the type-24 source at 50 microsecond, a train of pulses at 20 kHz can be generated. The phase angle of these pulses is controlled by changing the threshold, VREF.1, which can be the output of a phase-angle-control (PAC) control scheme. The width of the firing pulse is controlled by changing the time delay PULWID,which can be the output of a pulse-width-modulated (PWM) control scheme.

A PAC MIU consists of two Mapham inverters connected as shown in Figure 5 [7]. The inverters are connected in parallel on the dc side. Capacitors are added in series to the ac outputs to improve voltage regulation. The inverter ac outputs are then combined through a transformer to provide a total output voltage of 440 V RMS.

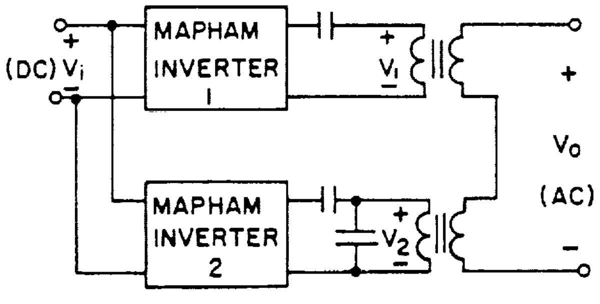

Figure 5. Phase-angle-controlled MIU

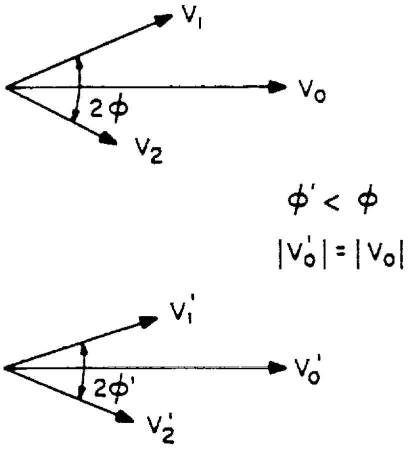

Figure 6. Voltage control mechanism performed by the PAC MIU

The PAC MIU is simulated with EMTP and is incorporated in the system model shown in Figure 1. Besides dc/ac power conversion, the MIU is also designed to control the voltage at bus 1. Voltage control is achieved by changing the two inverter output voltages. The voltage control mechanism is illustrated in Figure 6. By changing the angles $+\Phi$ and $-\Phi$, the resultant voltage can be maintained at the designated 440 V, even though the two constituent voltages are changed to accommodate different system operating conditions.

The voltage control system modeled with TACS is shown in Figure 7. The RMS value of the measured voltage is compared with the reference voltage to generate a voltage error signal. The error signal is fed to an integral control block to produce change in phase shift (required for corrective control) which, in turn, is fed to the pulse firing circuits of the Mapham inverters.

The dynamic response of the PAC MIU to a step load change from 5 kW to 2 kW is shown in Figure 8. While the load current is reduced, the voltages at bus 1 and bus 3 are regulated back to 440 V within four cycles. Both the magnitude and the phase angle of the two inverter output voltages are changed in the course of control actions.

B. Pulse-width-modulated (PWM) MIU

The basic component is a PWM resonant inverter circuit as shown in Figure 9. This circuit is a modified version of the circuit developed by TRW [8], although both circuits function in similar manner. The basic resonant tank consists of an inductor and a capacitor. The latter is connected in parallel to a center-tapped transformer. The voltage is stepped up by the transformer and the voltage harmonics are filtered out by a harmonic trap. The output voltage is a 20 kHz waveform with very little amount of harmonics. Any load connected to the inverter output is functionally connected in parallel to the capacitor.

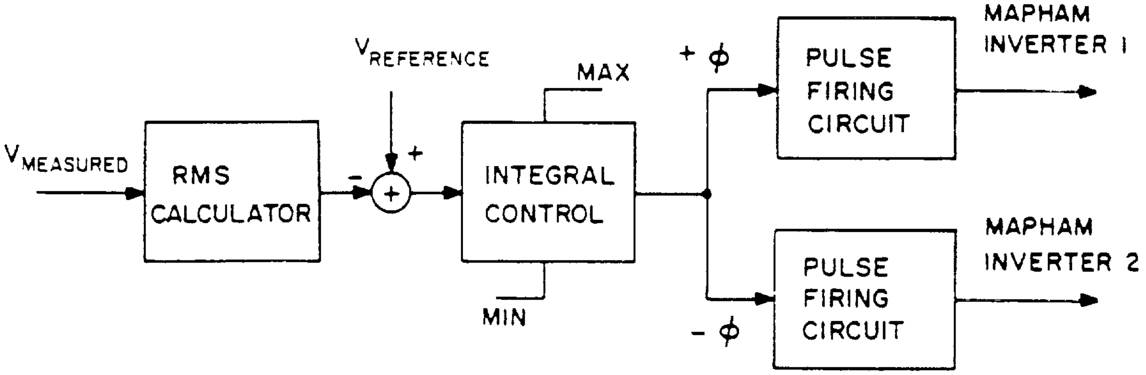

Figure 7. PAC MIU Voltage Control System modeled with TACS

The resonance frequency, *fr*, is determined by the values of L, C, and the load. The operating frequency of the output voltage, *fo*, is determined by the frequency at which the transistors are turned on and off, provided that the ratio, *fr/fo,* is greater than unity. Thus, *fr/fo* is an important design parameter.

The steady-state operating cycle of this circuit consists of the following sequence of operating modes.

Mode 1 : Q3 is turned on and Q2 is turned off ; current flows from the dc source to the capacitor through D1 and Q3 and charges the capacitor in the positive direction.

Mode 2 : Q1 is turned on and Q3 is turned off ; current circulates through D1, Q1, and the resonant circuit.

Mode 3 : Q4 is turned on and Q1 is turned off ; current flows from the dc source to the capacitor through D2 and Q4 and charges the capacitor in the negative direction.

Mode 4 : Q2 is turned on and Q4 is turned off ; current circulates through D2, Q2, and the resonant circuit.

The amount of power delivered by the inverter is determined by the durations of mode 1 and mode 3 in the operating cycle. These durations are determined, in turn, by the width of the base current pulses applied to transistors Q3 and Q4. Circuit control is achieved through pulse-width-modulation (PWM).

The operation of PWM inverter has been simulated with EMTP and the results are shown in Figure 10. These results are consistent with those obtained experimentally. The operating frequency is 20 kHz and the ratio *fr/fo* is about 2.0. The present version of EMTP does not have explicit models for transistors. However, transistor operation can be modeled using the TACS-controlled switches (TCS). When a TACS signal supplied to a TCS becomes positive, the TCS is turned on. TCS is turned off when the same TACS signal becomes negative. Using a scheme similar to one shown in Figure 4, pulses with controllable pulse width are generated at a frequency of 20 kHz and are used to control the transistors. The rest of the circuit, including the center-tapped transformer, can be readily modeled using available EMTP features.

A PWM MIU model is incorporated in the system model shown in Figure 1. Voltage control is achieved by changing the width of the transistor base current pulses. The voltage control system modeled with TACS is shown in Figure 11. The RMS value of the measured voltage (at bus 1) is compared with the voltage reference to produce a voltage error signal. This signal, processed by a proportional-integral (PI) control scheme, changes pulse width (required for corrective control) which is fed to the pulse firing circuit of the inverter.

The dynamic response of the PWM MIU to a step load change from 5 kW to 2 kW is shown in Figure 12. The pulse width is reduced to handle the load change and the voltage at bus 3 is regulated back to 440 V RMS within eight cycles.

Using the Fourier analysis feature of EMTP, harmonic distortions produced by power electronics can be examined. EMTP results indicate that the harmonic distortions generated by PWM MIU vary with power output levels. Table 2 presents the voltage harmonics at the harmonic trap input (point A in Figure 9) for two different power levels. The higher harmonic contents at lower power levels could have adverse effects on the performance of the control system.

The selection of simulation time-step size is based on the tradeoff between accuracy and computation time. A fixed time-step size of 0.1 microsecond (0.72 electrical degree) is found to be sufficient to accurately model the 20 kHz power electronic systems. Experience suggests that a time-step size in the order of 1 electrical degree is a good rule-of-thumb.

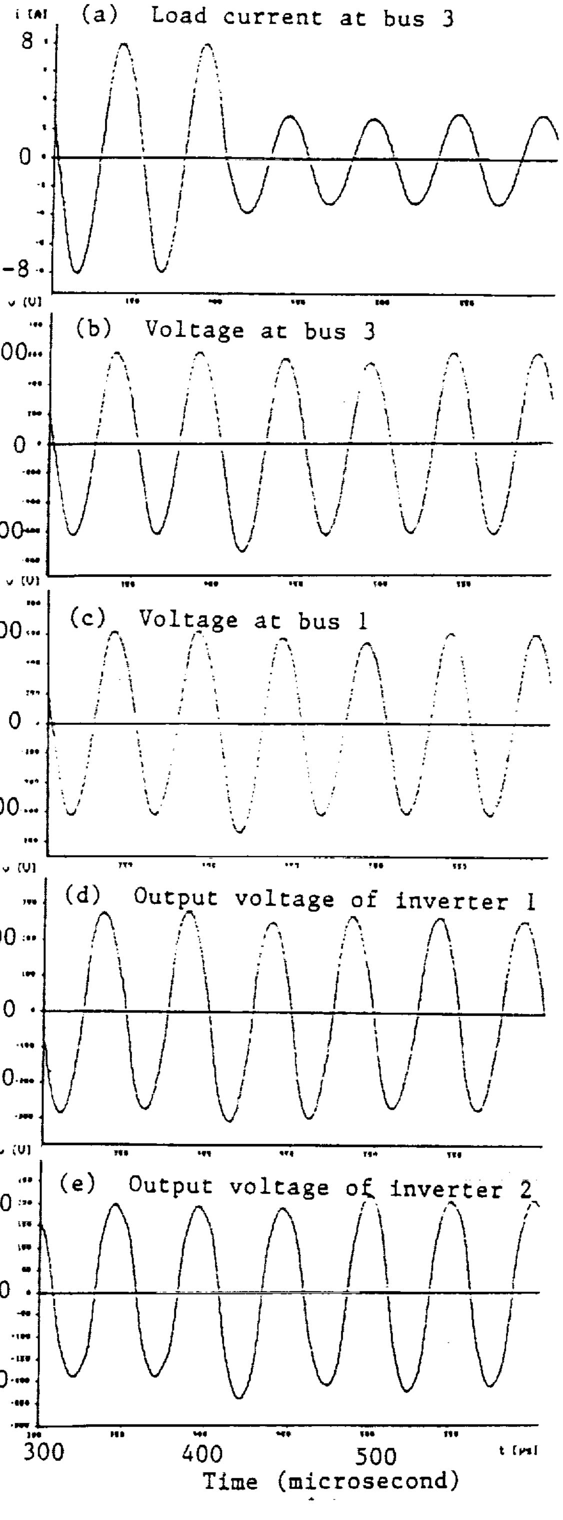

Figure 8. Dynamic Response of the PAC MIU to a step change of load

4. APPLICATIONS OF EMTP

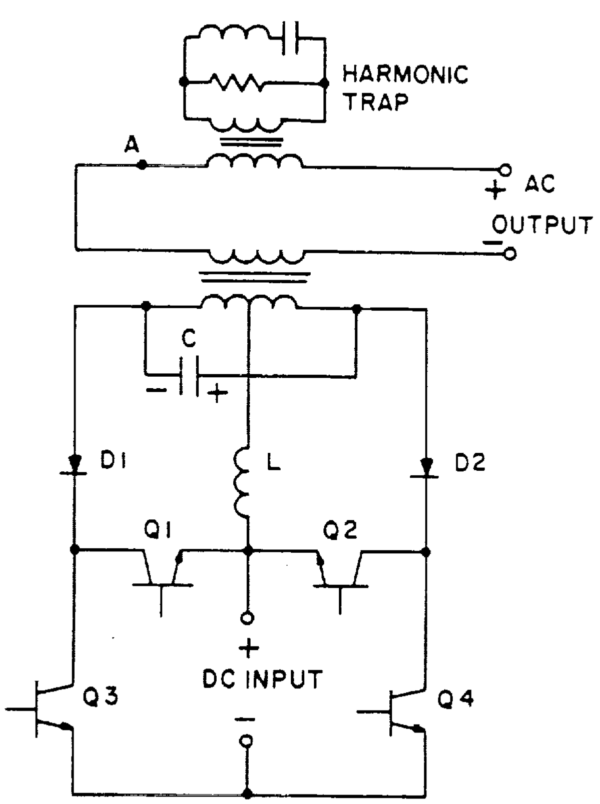

Figure 9. Pulse-width-modulated resonant inverter

With its present features, EMTP can be used to support the following modeling activities, which, in turn, could be used for purposes such as teaching, design, analysis, research, etc.

1. **Simulation of steady-state and transient behavior.**

Good understanding of the behavior of components, circuits, and systems in different situations may be gained using EMTP simulations.

2. **Experimentation with new ideas and evaluation of alternatives.**

Harmonic number	5 kW (%)	2 kW (%)
0	0.2	0.9
1	100.0	100.0
3	6.4	7.2
5	0.8	2.0
7	0.4	0.8
9	0.4	0.4
11	0.2	0.3
13	0.1	0.2

Table 2. Voltage Harmonic levels at the harmonic trap input at two power levels

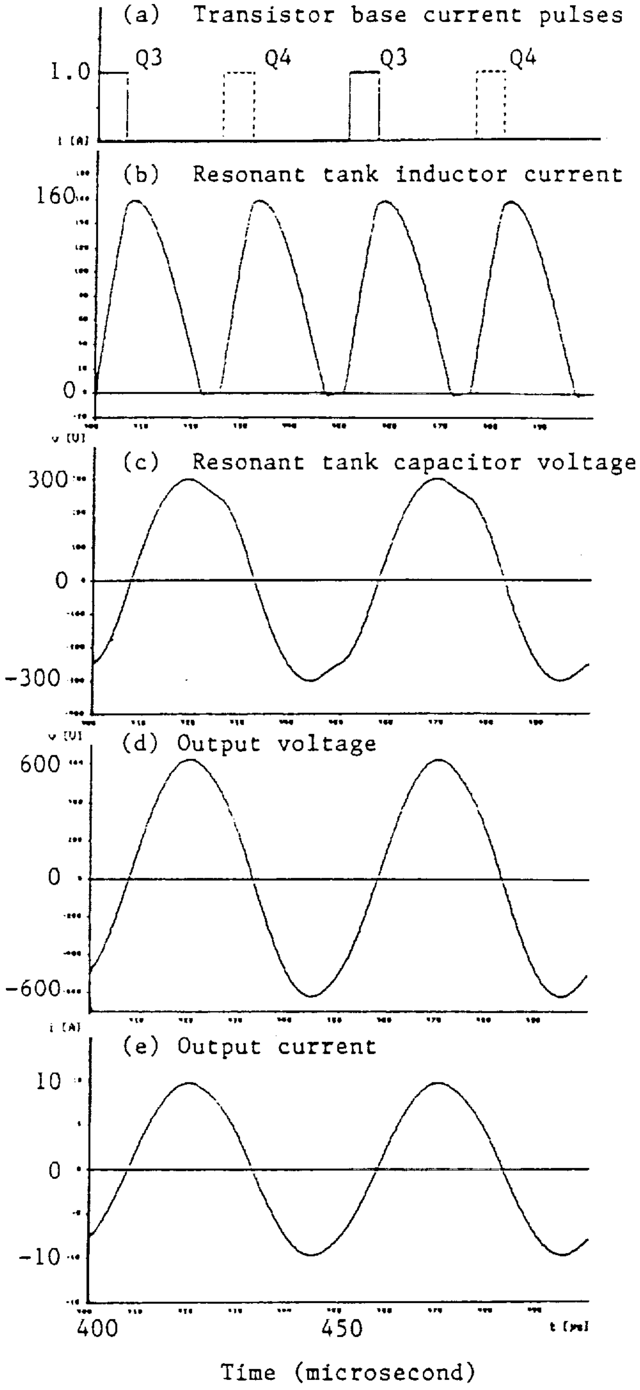

Figure 10. Steady State operation of PWM Inverter

EMTP simulation provides an inexpensive and convenient method to test new ideas and to compare alternatives for system components, system structures, and control schemes. For example, an experimental control/protection scheme was developed for the PAC MIU to enhance its performance during fault conditions. Upon detection of a fault, the scheme will force the two inverter voltages to be out of phase, resulting in a zero voltage at the MIU output. However, simulation indicates that this scheme requires inverters with a much higher current rating.

3. Obtaining information on equipment ratings.

EMTP simulation can provide information on the required ratings of various system components. For example, the blocking voltage requirement of SCRs in the PAC MIU can be determined by plotting the voltages across the SCRs.

4. Investigation of potential problems.

EMTP simulation can be used to identify potential problems and to study solutions. For example, EMTP simulation shows that the PWM MIU is vulnerable to open circuit conditions. This should be taken into consideration during the design of the protection system.

Instead of interfacing with TACS, the system modeled with EMTP can be monitored, operated and controlled using actual control hardware and/or software. Work is underway to integrate EMTP with real-time control for enhanced simulation, controller design, and on-site controller diagnostic [9]. EMTP may also be integrated with real-time control/protection expert system [10] for simulation and control verification.

5. CONCLUSIONS

This study demonstrates that power electronic systems can be modeled with EMTP. The technique used to model PAC and PWM circuits can be applied to model a wide variety of power electronic circuits. EMTP modeling is accurate and can support various modeling activities that are useful for teaching, design, analysis, and research associated with power systems and power electronics. Potential areas of applications include real-time control and expert systems.

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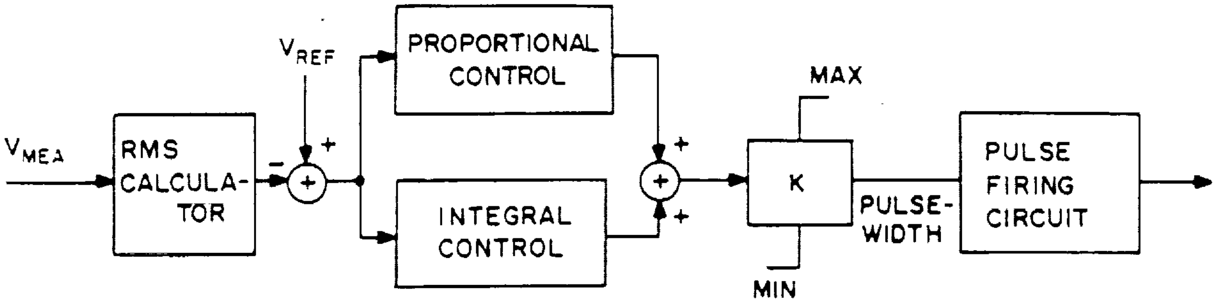

Figure 11. PWM MIU Voltage Control System modeled with TACS

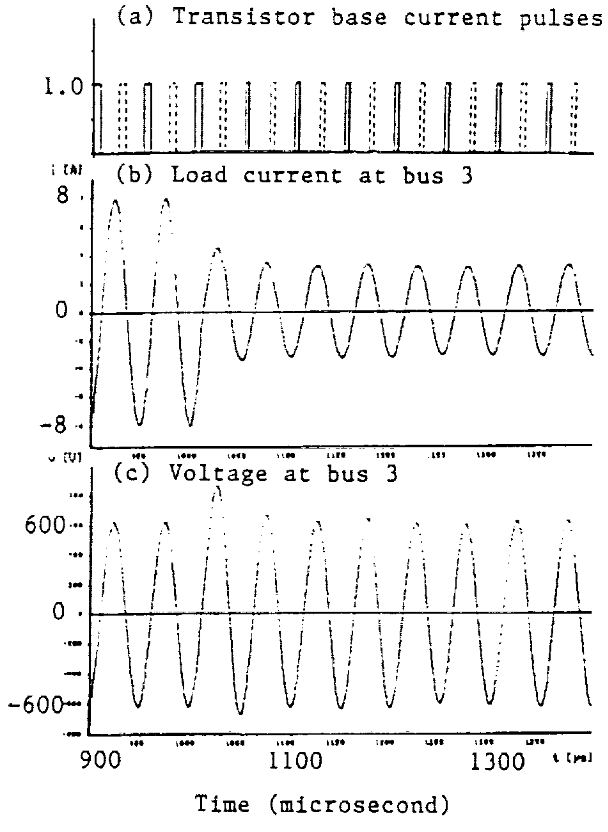

Figure 12. Dynamic Response of the PWM MIU to a step change in load

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16. Abstract

In view of the potential impact of power electronics on power systems, there is need for a computer modeling/analysis tool to perform simulation studies on power systems with power electronic components as well as to educate engineering students about such systems. This paper describes the successful modeling of the major power electronic components of the NASA Space Station Freedom Electric Power System, EPS, with EMTP (ElectroMagnetic Transients Program) and demonstrates that EMTP can serve as a very useful tool for teaching, design, analysis, and research in the area of power systems with power electronic components. The paper describes EMTP modeling of power electronic circuits and presents simulation results.

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