Design of a microcontroller-based passive standby uninterruptible power supply

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Abstract This paper describes the design of a microcontroller-based passive standby Uninterruptible Power Supply (UPS), where the student applies a top-down systems approach to produce a working system. Such a project involves hardware–software co-design for realizing the relatively large number of detection, protection and control functions within the UPS.

Keywords hardware–software co-design; microcontroller; UPS

Uninterruptible Power Supplies (UPSs) are widely used for power conditioning applications, whereby the load is to be supplied with current and voltage waveforms containing minimal disturbance. A UPS also provides emergency power to critical loads in case of utility mains failure, and as such constitutes an essential element in providing back-up power[1] for computer networks, communication links, biomedical equipment, and industrial processes, among others. Full hardware-based UPSs are gradually being replaced by microprocessor or microcontroller-based counterparts, with significant improvement in ease of design, flexibility of the control software and overall reduction in development cost. Since a UPS incorporates a relatively large number of detection, protection and control functions,[2] it is important to develop an organised approach to the identification and implementation of these requirements. This paper presents a design project, where the student is required to use a top-down methodology for developing a passive stand-by microcontroller-based UPS system. The project also involves hardware–software co-design, so that knowledge from a number of engineering disciplines is necessary for arriving at a workable solution. In the process, the student realizes the advantage of logically analyzing the system requirements according to functional areas, rather than having subjective ideas of the solution at the beginning. The paper is organized as follows: the next section highlights the salient aspects of the top-down systems approach used in the development of such a project at final year undergraduate level. Illustration and evaluation of the proposed methodology for the development of a passive stand-by UPS are also presented.

Top-down systems approach

Figure 1 illustrates a generic top-down systems approach that students are expected to follow in their design projects. Starting from the given specifications, the fundamental problems that need to be solved are identified, without being influenced by pre-conceived ideas of what the solution might be. The problems

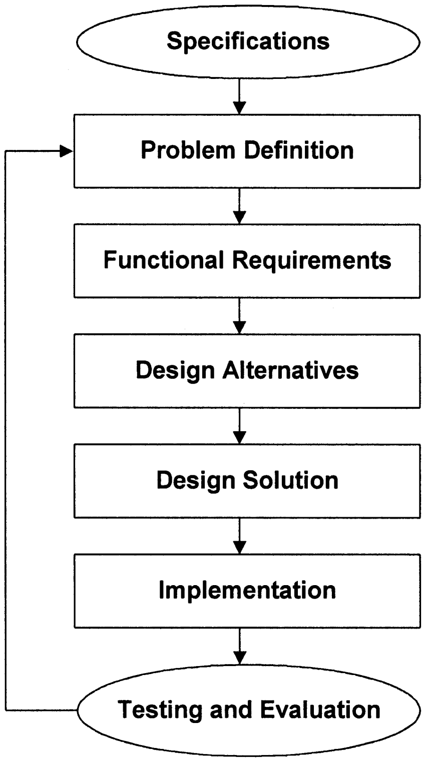

Fig. 1 *Top-down systems approach.*

at hand are further explored and decomposed into progressively more detailed functional requirements that need to be implemented. Next, a thorough analysis of the design alternatives for both hardware and software modules needs to be carried out. Thus, the proposed design should be justified according to predefined criteria such as functionality, size and cost of the final product. Since the present application involves the use of hardware and software components, the designer should be able to translate the functional requirements into an algorithm development, as well as circuit design schematics that reflect the proposed solution. An important aspect of the implementation stage is the identification of the hardware and software platforms that will support the final design. These involve the judicious choice of hardware components and programming language for coding the developed algorithm. Testing and evaluation aim at both verifying the performance of the implemented system against specifications, as well as confirming the validity of the initially defined problems. Any mismatch in the validation and verification processes should be corrected by modifying the problem definitions, introducing new system requirements, considering other design alternatives, or refining the existing solution.

Passive stand-by UPS design

A block diagram of the passive stand-by UPS, which provides the essential functions of power conditioning and power back up, is shown in Fig. 2. Power conditioning involves the suppression of the effects of line disturbances, typically over-voltages, blackouts, brownouts, spikes, surges and electromagnetic interference. Back-up power coverage is necessary for providing continuous power flow to the critical load, when the utility mains cannot reliably supply the load. In this case, power is delivered to the load by the auxiliary source of energy, through the power converter stage. Development of the overall system calls for expertise in various areas of electrical engineering, namely power electronics, electronic system design, circuit theory, microcontroller programming and interfacing, and instrumentation. Modules covering these subject areas are thoroughly covered during the first two years of a BEng (Hons) course in electrical and electronic engineering, and hence offer the necessary pre-requisites for undertaking the project at final-year level. Above all, the project work is backed by systems engineering lectures, where the student is exposed to the structured approaches[3–5] for problem solving, through case studies. In the process, students become proficient in all aspects of the design, implementation and testing phases for both hardware and software-based systems.

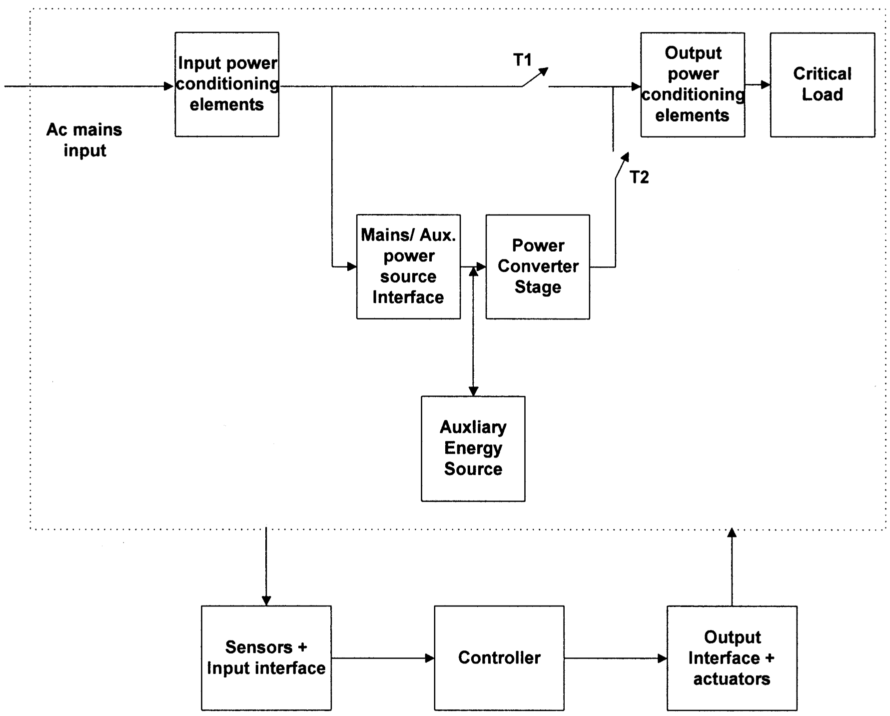

Fig. 2 *Block diagram of passive stand-by UPS.*

Specifications

The student is initially given the main design specifications for the microcontroller-based UPS as follows:

Stand-by power rating: 150 V A
Nominal load voltage: 230 V a.c., single phase, 50 Hz
Auxiliary source voltage: 24 V d.c.
Autonomy time: 30 minutes
Line disturbances to be suppressed: sags, blackouts and over-voltages
Mains a.c. supply: 230 V, single phase, 50 Hz
Maximum transfer time: 8 ms
Maximum THD in load voltage: 3%

Problem definition and functional requirements

Figure 3 illustrates the functional requirements in the development of the UPS system. The designer is confronted with two fundamental problems, namely (i) providing continuous power to a critical load, such as a PC, and (ii) suppressing the effects of disturbances on the power lines between the supplies

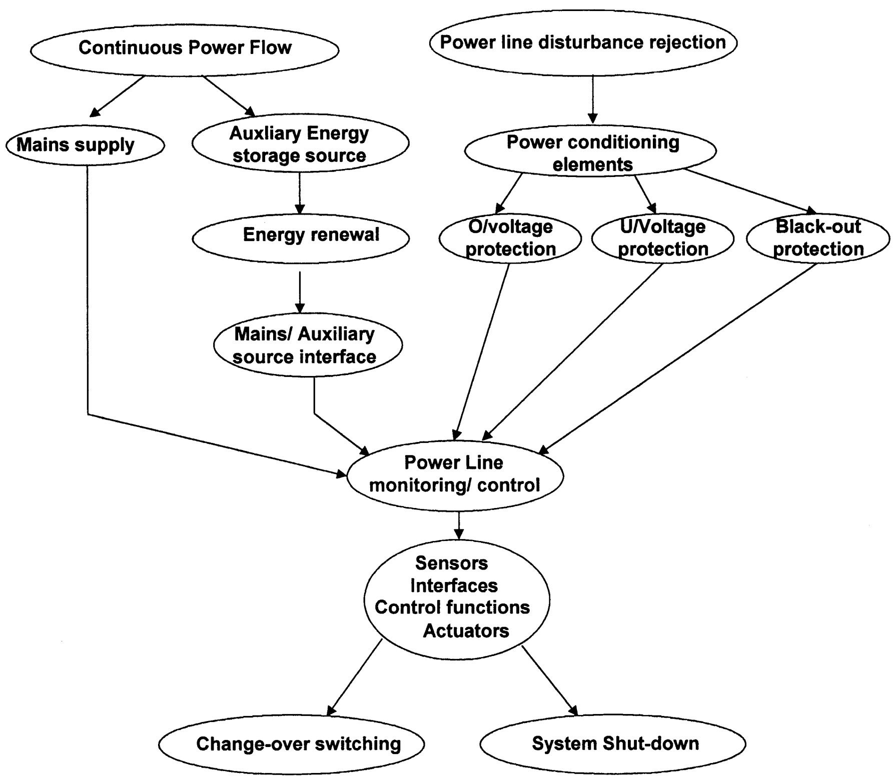

Fig. 3 *Functional requirements for UPS system.*

and the load. Continuous power flow implies the need for a secondary energy storage device to replace the utility mains in case the latter fails. Energy taken from the secondary source is replenished from the mains when the latter is restored. Hence, a power interface is necessary between the a.c. supply and the back-up source. Moreover, power flow needs to be controlled from the secondary source so as to match the load requirements in terms of output voltage, current and frequency.

On the other hand, power-conditioning elements are necessary for overcoming the possible disturbances present on the lines feeding the critical load. These elements have to take into account the types of disturbances that need to be overcome in the present system from the given specifications. Hence, one fundamental requirement for this function is the continuous monitoring of current and voltage on the power lines at points where protection is to be offered, thus implying the need for sensors and interface circuitry to the microcontroller. When line data is acquired, control decisions should be taken at the microcontroller level with the aim of actuating appropriate changeover or shutdown circuitry and power conditioners.

Design and implementation

Once the functional requirements of the UPS system have been established, the design alternatives at each stage can be identified. For instance, a battery set and a capacitor bank stand as possible candidates for implementing the auxiliary energy source. However, for the specified UPS autonomy time, the use of a 24 V sealed type battery represents a more economical solution for providing a controlled shutdown of the load in the event of a mains failure. A d.c. to a.c. inverter is required for interfacing the battery output to the load, as shown in Fig. 4. A sinusoidal Pulse Width Modulated (PWM) single-phase bridge inverter is chosen, and its power switches are implemented using Insulated Gate Bipolar Transistors (IGBTs), with the aim of achieving a relatively high switching frequency for reducing the size of the output filter components. The changeover switches, T1 and T2 in Fig. 2, are implemented using triacs so as to minimise the transfer times between the mains and the battery, or vice-versa.

Figure 5 shows the flowchart for the UPS control algorithm. The corresponding program is coded in assembly language for the PIC18C252 microcontroller. The a.c. input line is continuously monitored for detecting over-voltage, sags and blackout conditions. The load is transferred to the battery bank through the inverter, only if the duration of the line disturbance exceeds a preset value, so as to avoid nuisance switchings between the mains and the battery. In case the battery is not sufficiently charged to supply the load during a mains failure, the UPS is shut down by turning off triacs T1 and T2 in Fig. 4.

In the back-up mode, the sinusoidal PWM inverter control routine is executed so as to switch the inverter IGBTs for low-distortion output voltage specified at the load terminals. Battery charging from the mains is achieved by using a half-controlled thyristor bridge a.c. to d.c. converter which can operate

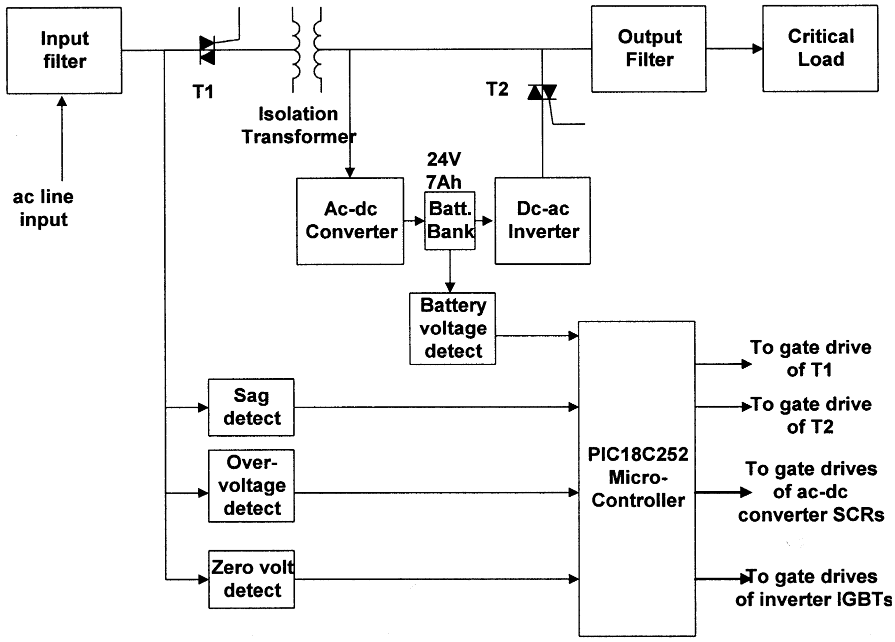

Fig. 4 *Block diagram of implemented UPS.*

in two modes, namely trickle charging when the battery voltage has reached the float value, and full charging when the mains has recovered following a line disturbance. The microcontroller program selects the correct operating mode, depending on the battery voltage detector output.

System integration and testing

A modular approach[6,7] is also used in the testing phase of the implemented system. Tests are performed at three levels, namely on the hardware modules, the software components and the final embedded system which integrates the hardware and software. By using this approach, the student can quickly and effectively locate any source of error or fault condition and take necessary corrective measures at the relevant level of the design process. To avoid damage to the microcontroller, the detector circuits connected to the a.c. input lines are tested separately to verify the output logic levels and electrical isolation. The a.c.–d.c. converter and d.c.–a.c. inverter are initially tested with laboratory-based experimental trigger modules to confirm reliable operation of each power circuit. Next, the software modules developed for the UPS control are tested by emulating each detector output signal as logic levels on the microcontroller interrupt lines, and verifying the controller output for each input combination. The generation of trigger pulses for triggering the triacs, thyristors of the battery charger and IGBTs in the inverter can thus be checked. The microcontroller interface, detector and power circuits are finally integrated and the

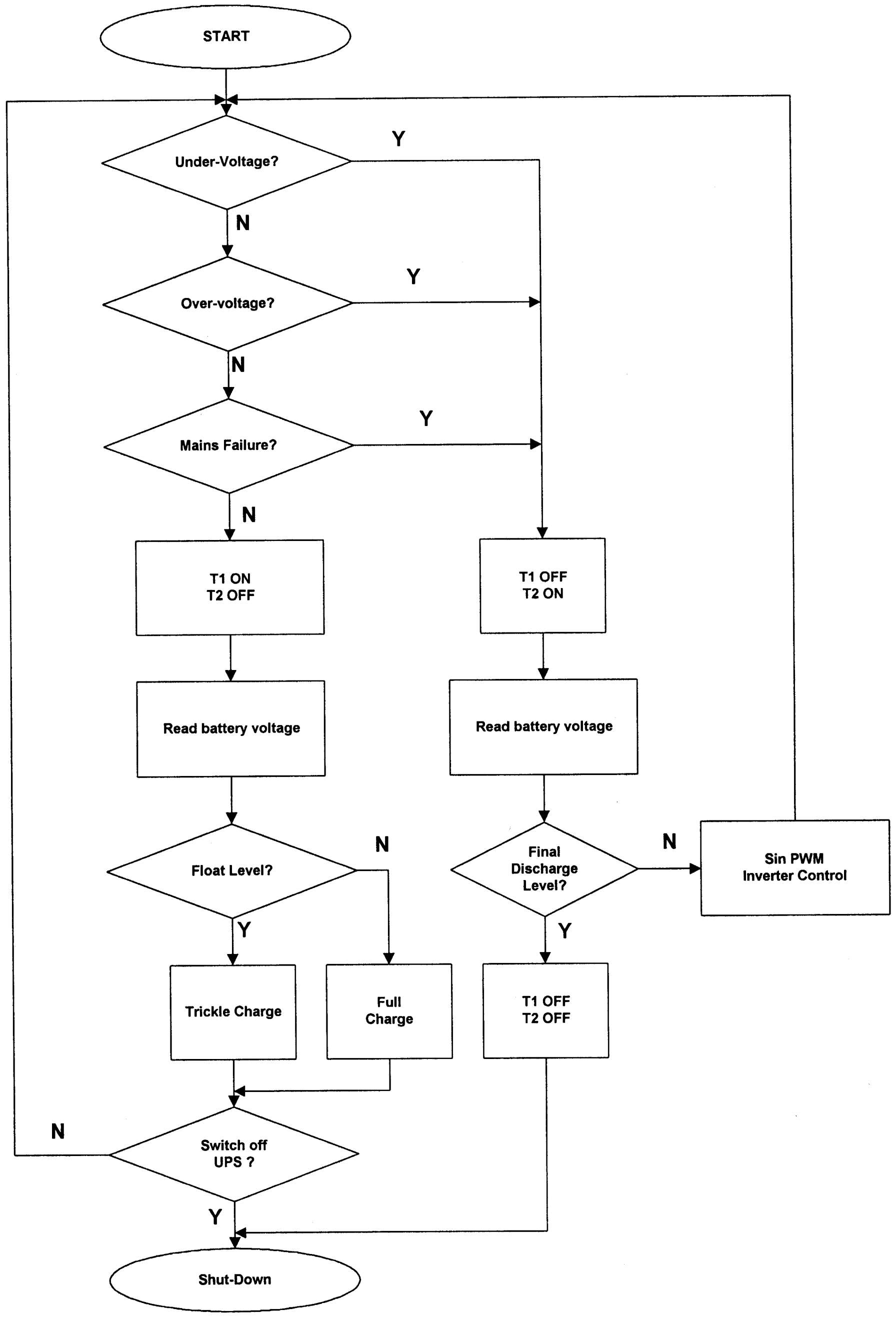

Fig. 5 *Flowchart for UPS control.*

operation of the overall system is verified against the specifications and functional requirements.

Evaluation of systems approach

One major objective of the design project is to develop students' skills so that they become proficient in all aspects of the development process, from problem definition and identification of requirements, to planning, design, implementation and testing of the proposed solution. The other key objective is to make students master hardware and software development tasks and methodologies so that they acquire the necessary competence by the time they enter the job market as fresh engineers. The results of assessments by both project supervisors and external examiners, and feedback from past graduates tend to confirm the effectiveness and appreciation of the proposed systems approach for project design and implementation. Course evaluations also indicate better students' satisfaction with the adopted methodology with such design projects. Moreover, the positive impact on students' achievements has also boosted their interest in postgraduate courses and research.

Conclusion

In this paper, the design of a passive stand-by UPS has been presented with the aim of illustrating the top-down systems approach that students are encouraged to use when working on their final year projects. Such a methodology has been well received by students and helps them realise that the formulation of a solution to a design problem can be done effectively by applying structured solving techniques. The objective of enhancing their hardware and software design skills has also been attained to a large extent. By focusing on this type of approach, the knowledge and capabilities acquired can readily be transferred and applied to more complex projects.

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