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A system for inverter protection and real-time monitoring

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Abstract

A real-time system for protecting and monitoring a DC/AC converter has been designed and constructed. The proposed system consists of (a) a hardware protection unit for fast reaction, load protection and inverter fail-safe operation and (b) a microcontroller unit for calculating critical parameters of the inverter operation. The control unit malfunctions have not been investigated in this study. The proposed hardware architecture and sensors form a low-cost and reliable control unit. The experimental results show that the proposed system ensures the inverter protection and fail-safe features. The proposed unit can be used to increase the reliability of any power inverter in AC motor drives, renewable energy systems, etc. or can be incorporated in any UPS system.

Keywords: Real-time system; DC/AC inverter; Fail-safe; Protection; Microcontroller

1. Introduction

DC/AC power converters (inverters) are used today mainly in uninterruptible power supply systems, AC motor drives, induction heating and renewable energy source systems. Their function is to convert a DC input voltage to an AC output voltage of desired amplitude and frequency. The inverter specifications are the input and output voltage range, the output voltage frequency and the maximum output power.

An inverter is required to:

1. always operate within its strict specifications, since the inverter may supply power to sensitive and expensive equipment,
2. fail-safely in case of malfunction, since inverters are often used in harsh environments to electronics, for example, outdoors in case of renewable energy applications with wide temperature and humidity variations and
3. record the inverter state and inform the supplied equipment and/or the operator about the cause of failure.

Considering the inverter protection, the designers usually employ special protection devices and control circuits. The most common form of overcurrent protection is fusing [1], but this method is not always effective because fuses have relatively slow response-time, so additional protective equipment is required, such as crowbar circuits or a d*i*/d*t* limiting inductance. The DC supply and load-side transients can be suppressed with filters, which have the disadvantage of increasing the inverter power losses, cost and weight.

Current source inverters (CSI) have an inherent overcurrent protection capability, since proper design of the DC link inductance can provide protection against overload conditions [2]. Voltage source inverters (VSI) include an L-C filter at the output stage thus, in case of an output short-circuit condition, the filter inductance limits the output current rising rate [3]. In both preceding cases, the high inductance value leads to inverter size and power losses increase. A commonly used protection circuit is shown in Fig. 1 [4]. The inverter output current, load voltage and filter capacitor current are sensed and compared to preset limits. If any of the above quantities exceeds the preset limits, an inhibit signal shuts off the DC power supply.

In motor drive applications, the inverters are usually protected only from overloading conditions, using either intrusive current sensing techniques, which measure the DC

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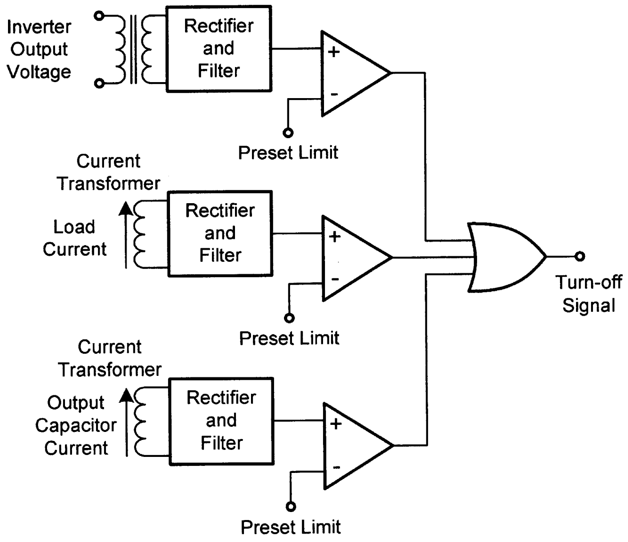


Fig. 1. An inverter protection circuit.

input current or the load current [5–7] or special motor control algorithm techniques [8–10]. However, the above methods do not fully detect all possible fault conditions, e.g. a DC link capacitor short circuit [11].

The advance of the microcontroller technology has led to the implementation of digital control techniques for controlling and monitoring inverters. The use of a Kalman filter for monitoring the magnitude and frequency of a UPS output voltage is proposed in Ref. [12]. Although this method has the advantage of integration of a number of control functions in a single chip, it is not adequate for protection of the inverter from many kinds of faults. If this method is extended to monitor more critical signals, then the system response becomes not fast enough to protect the inverter, while the use of a faster microcontroller or a digital signal processor (DSP) increases the system cost.

Several methods have been proposed for fault detection on an inverter. A diagnostic system for the detection of faults of the power switches using output current sensors in a PWM inverter supplying a synchronous machine is presented in Ref. [13]. It is based on the analysis of the current-vector trajectory and of the instantaneous frequency in faulty mode. An expert-system-based fault diagnosis and monitoring method for a VSI is presented in Ref. [14]. The above-mentioned methods intend to assist the system operator to diagnose the inverter malfunction or damage after its occurrence.

In all above methods can be noted that most inverters do not fully fulfill the previously stated inverter requirements (steps 1–3). In this paper, the development of a low-cost control unit for protecting and monitoring a DC/AC inverter is presented. The proposed system consists of:

(a) a hardware protection unit, which compares the appropriate signals at specific points of the inverter circuitry with predefined levels, in order to determine the proper system operation, and
(b) a microcontroller-based, real-time system, which monitors all critical parameters of the inverter operation and displays them to the system operator in real-time.

In case of malfunction, the hardware protection unit immediately turns-off the inverter ensuring the fail-safe feature, while the microcontroller unit informs the system operator about the malfunction conditions. The microcontroller unit communicates with a computer through an RS-232 protocol. The necessary inverter parameters are measured with non-intrusive and non-dissipative sensors so that the inverter operation and specifications are not affected. The microcontroller-based implementation is preferred over a faster DSP because of its lower cost. However, a DSP would be a favourable solution in case that additional control functions (i.e. power semiconductors control, advanced battery monitoring algorithms, etc.) are to be digitally implemented. The control unit malfunctions have not been investigated in this study.

This paper is organised as follows: the inverter hardware and causes of failure are explained in Section 2; the sensors and actuators required to detect problems on time and force the inverter to shut down are explained in Section 3; the proposed control and monitoring unit is presented in Section 4; the microcontroller algorithm is analysed in Section 5, while the experimental results are presented in Section 6.

2. Inverter hardware and causes of failure

An inverter general diagram is shown in Fig. 2. A bridge built around IGBTs modulates the DC input voltage to a sinusoidal pulse width modulated wave (SPWM). A low-pass, LC-type filter is used to demodulate the SPWM to a sinusoidal waveform, while a power transformer is used to produce the required high voltage, low-distortion output (e.g. 220 V, 50 Hz). Alternatively, the power bridge can be built around power MOSFETs [15], depending on the inverter power capability, the DC input voltage value and the desired efficiency.

The problems that may occur during the inverter operation are the following [3,11]:

- input voltage outside the inverter specifications,
- overloading conditions,
- output overvoltage transients, e.g. when connecting or disconnecting motors,
- output short-circuit condition,
- output voltage amplitude and frequency outside the inverter specifications,
- high ambient temperature, which changes the power semiconductors characteristics,

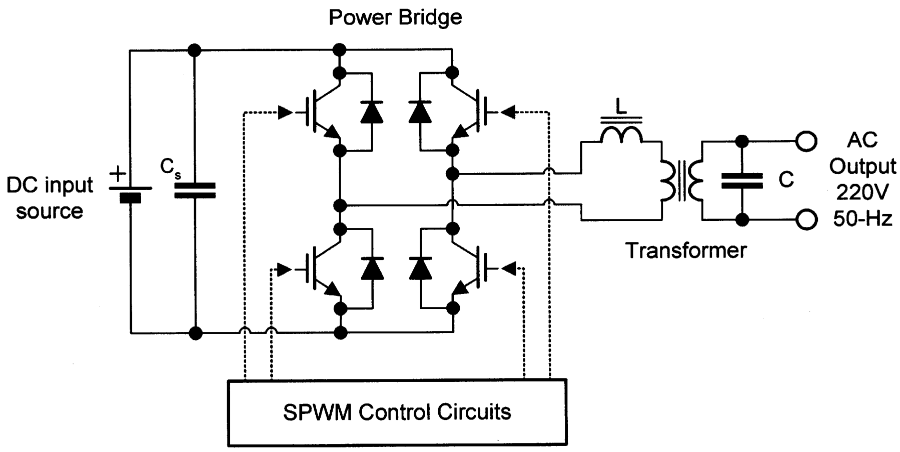


Fig. 2. A general diagram of an SPWM single-phase inverter.

- high humidity which may affect the electronic parts behavior and finally
- other unexpected factors, e.g. faults on the inverter driving circuit, etc.

If any of the above-mentioned problems occurs, the inverter must be shut down immediately in order to protect the load and the inverter power conversion stages from destruction, while the system operator must be informed accordingly about the problem. The mean time between failures (MTBF) for inverters is of the order of several 10,000 h, [9].

3. The sensors

The position of the sensors on the inverter is shown in Fig. 3. Hall-effect-based sensors are used to measure the DC input current and the AC output current. They have advantages compared to shunt resistors, such as isolation from the main power circuit and independency of their characteristics from dust, humidity and time. Also, they feature wide frequency bandwidth, including DC operation and low temperature variation of their characteristics, so they are ideal for current detection on PWM inverters [16,17]. The operation of the Hall-effect sensors without feedback ensures low power-consumption. But, since they response relatively slow cannot protect effectively the power bridge semiconductors from overcurrent conditions. Thus, an overcurrent protection circuit is developed for the protection of every set of parallel-connected MOSFETs, as shown in Fig. 4(a). Referring to this figure, the Q_1 (IRF530) is the power MOSFET to be protected, while the small-signal MOSFET Q_2 (BS170) prevents wrong reaction of the protection circuit if high voltage appears at the drain during the power MOSFET turn-off state. Under overcurrent conditions, the following inequality holds:

$$I_D \cdot r_{DS,on} \cdot \frac{R_2}{R_1 + R_2} \geq V_{BE} \qquad (1)$$

where I_D and $r_{DS,on}$ are the power MOSFET current and on-state resistance, respectively, while V_{BE} is the transistor Q_3 base-emitter voltage.

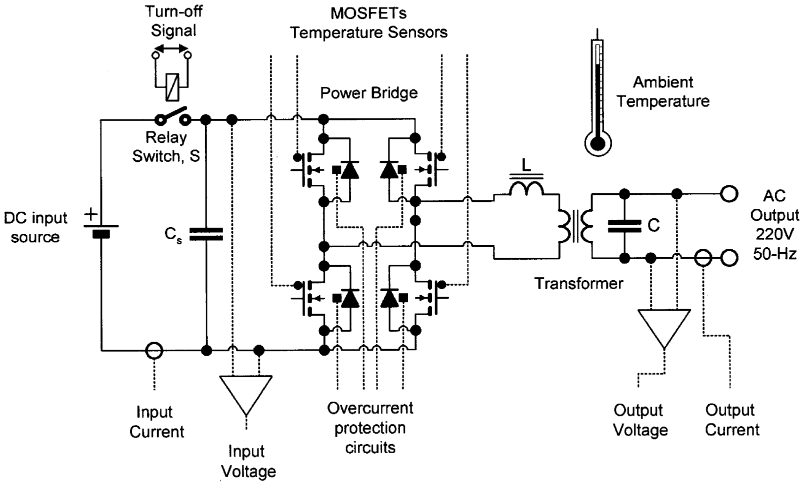
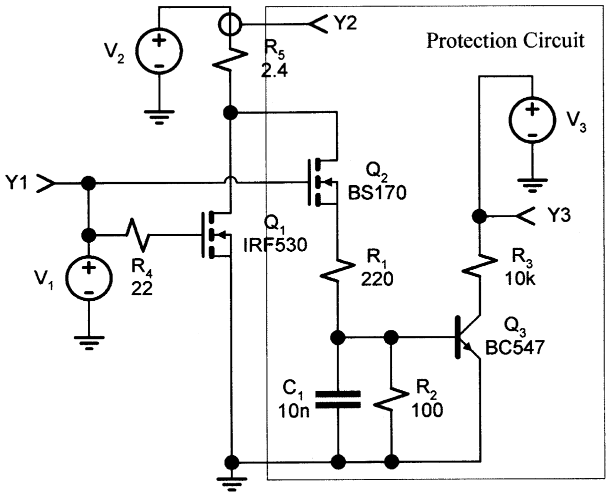
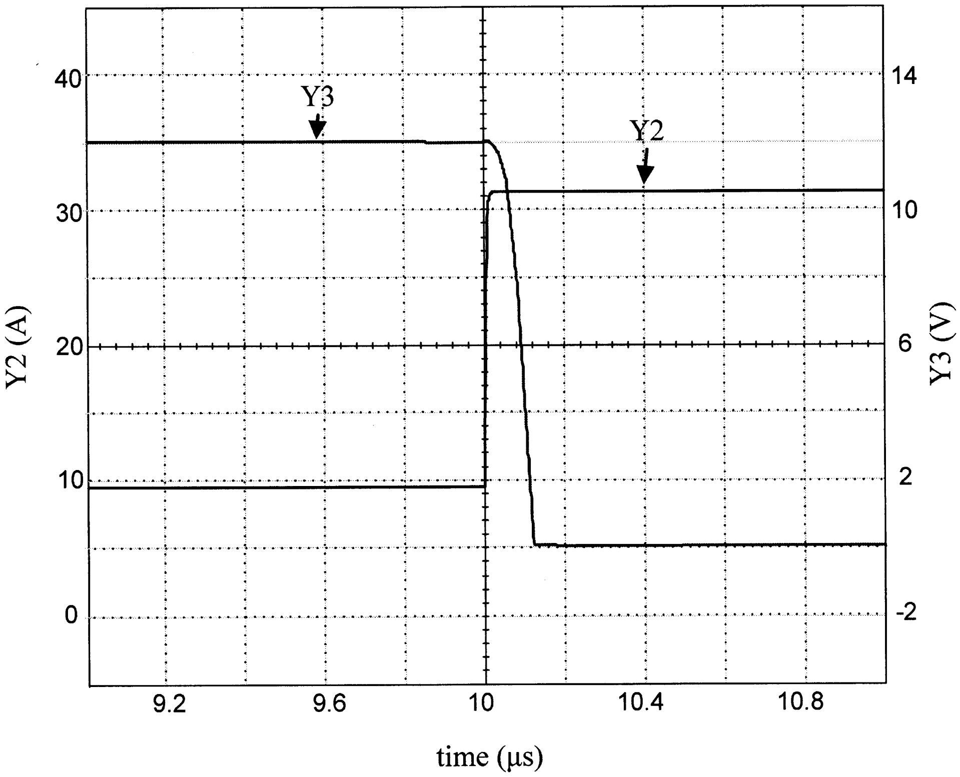


Fig. 3. The sensors and actuators on the inverter.



(a)



(b)

Fig. 4. The MOSFET protection circuit: (a) the schematic diagram and (b) the simulated output voltage waveform (Y3) for a step increase of the MOSFET current (Y2).

The operation of the above-described protection circuit is simulated using the IS-SPICE program. The results are shown in Fig. 4(b), where Y2 is a step change of the Q_1 power MOSFET current and Y3 is the protection circuit output voltage. It can be observed that the protection circuit output voltage drops to zero in about 100 ns. If this voltage is used to drive the MOSFET, the turn-off process takes place within about 500 ns, from the occurrence of the overcurrent condition, for this particular MOSFET. Since the power MOSFET peak current capability is much higher than its average rating and the current rise time is further limited by the inverter circuit inductances, this protection circuit is considered adequate for overcurrent protection of the MOSFETs. In cases where the DC input voltage is high, the inverter design can be based on alternative semiconductor devices such as IGBTs or BJTs, which are characterised by negative saturation voltage temperature coefficient. In such case, the protection circuit described above can be used to measure the voltage developed across a current shunt connected in series with the power switch.

An IC instrumentation amplifier is used to measure the AC output voltage, providing high input-impedance, high common-mode rejection and good temperature stability. A voltage divider followed by a unity-gain isolation amplifier (voltage follower) is used to measure the DC input voltage, protecting the inverter from malfunctions associated with either the DC input power source or the DC link capacitor. In addition, power semiconductor switches are occasionally subjected to overvoltages during the inverter operation. Such conditions are appropriately treated during the inverter design phase, by employing special circuits (e.g. RC snubbers) depending on the inverter topology requirements.

An IC temperature sensor is used to measure the ambient temperature. Its output voltage is proportional to temperature, while offering good linearity in a wide temperature range with high accuracy. Also, negative temperature coefficient (NTC), low-cost thermistors are used to monitor the temperature of the inverter power MOSFETs.

An electromechanical switch (relay, switch *S* in Fig. 3) is used to isolate the inverter from the DC input source, in case the input voltage exceeds the maximum limit of the inverter specifications.

4. Description of the protection and monitoring unit

A block diagram of the detection and protection unit is shown in Fig. 5. The sensors described in Section 3 are used to measure the following parameters during the inverter operation:

- the AC output voltage and current,
- the DC input voltage and current and
- the ambient temperature.

The above measurements are interfaced to the microcontroller through its A/D converter channels. The microcontroller calculates the rms output voltage value, the output voltage frequency, the inverter load as a percent of the maximum permitted load, the DC input voltage and the ambient temperature. If a battery is used as the inverter DC input source, the microcontroller checks continuously the charge level of the battery, as well. The inverter DC input current, which is the battery discharging current, is monitored and the battery remaining operating time is estimated. A 2 × 16-character liquid crystal display (LCD) interfaced with the microcontroller informs the operator about the inverter parameter values.

Also, the above-mentioned sensor signals are compared with predefined thresholds and the results are stored in an external register-set consisting of latches. The output values of the MOSFETs overcurrent protection circuits are also stored in the register-set. During normal operation, all register-set bits are in logic state ‘1’, while in case of

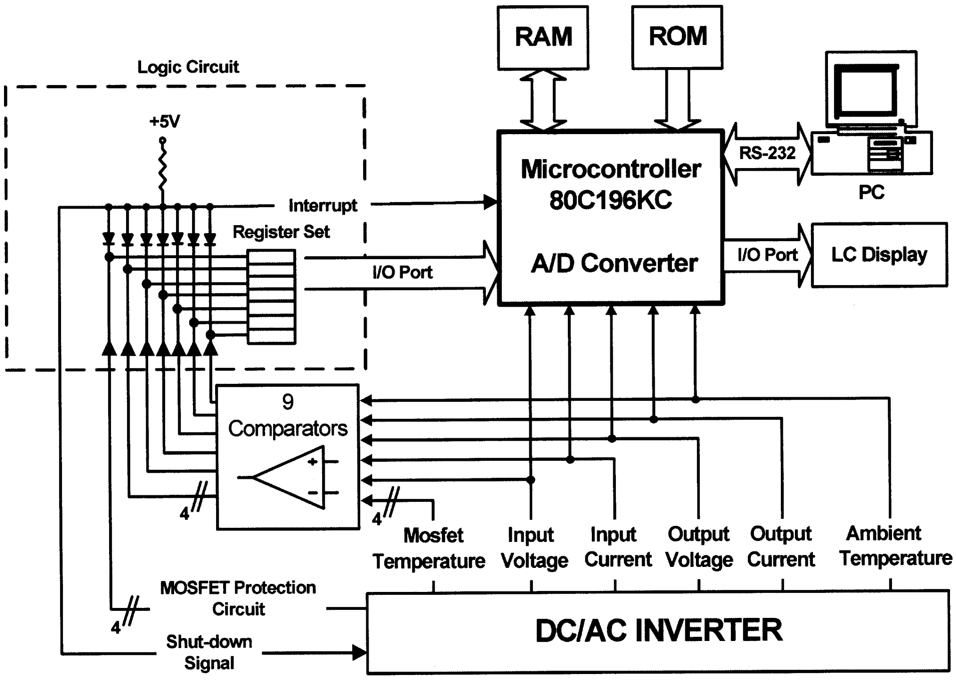


Fig. 5. Block diagram of the proposed control unit.

inverter specifications violation, the corresponding register-set bits are set to logic '0'. Then the hardware protection circuit turns-off the inverter and forwards an interrupt to the microcontroller, causing the check of the register-set bits one by one. The microcontroller parses the nature of the problem from the position of logic 0s in the register-set and informs the operator accordingly. In case of DC input overvoltage, the corresponding comparator output signal activates an electromechanical switch, as mentioned in Section 3.

The microcontroller used is the Intel 80C196KC with a 16 MHz clock. It has a 16-bit CPU, a 10-bit, 8-channel successive approximation A/D converter, a 4KB internal RAM, a 16KB internal EPROM and a serial communication port. This type of microcontroller features all characteristics required by the proposed system, such as an on-chip A/D converter, 16-bit architecture, high clock rate, low-power consumption and low cost. An additional 8KB static RAM and a 16KB EPROM are also installed on the microcontroller board for data and program storage. An RS-232 port interfaces the microcontroller with a computer, so that the operator can be informed in a more friendly and detailed way about the inverter operation state.

5. The microcontroller algorithm

The microcontroller algorithm flowchart is illustrated in Fig. 6. On start-up, all the microcontroller special function registers (SFRs) and the program variables are initialised. From then on, the microcontroller continuously

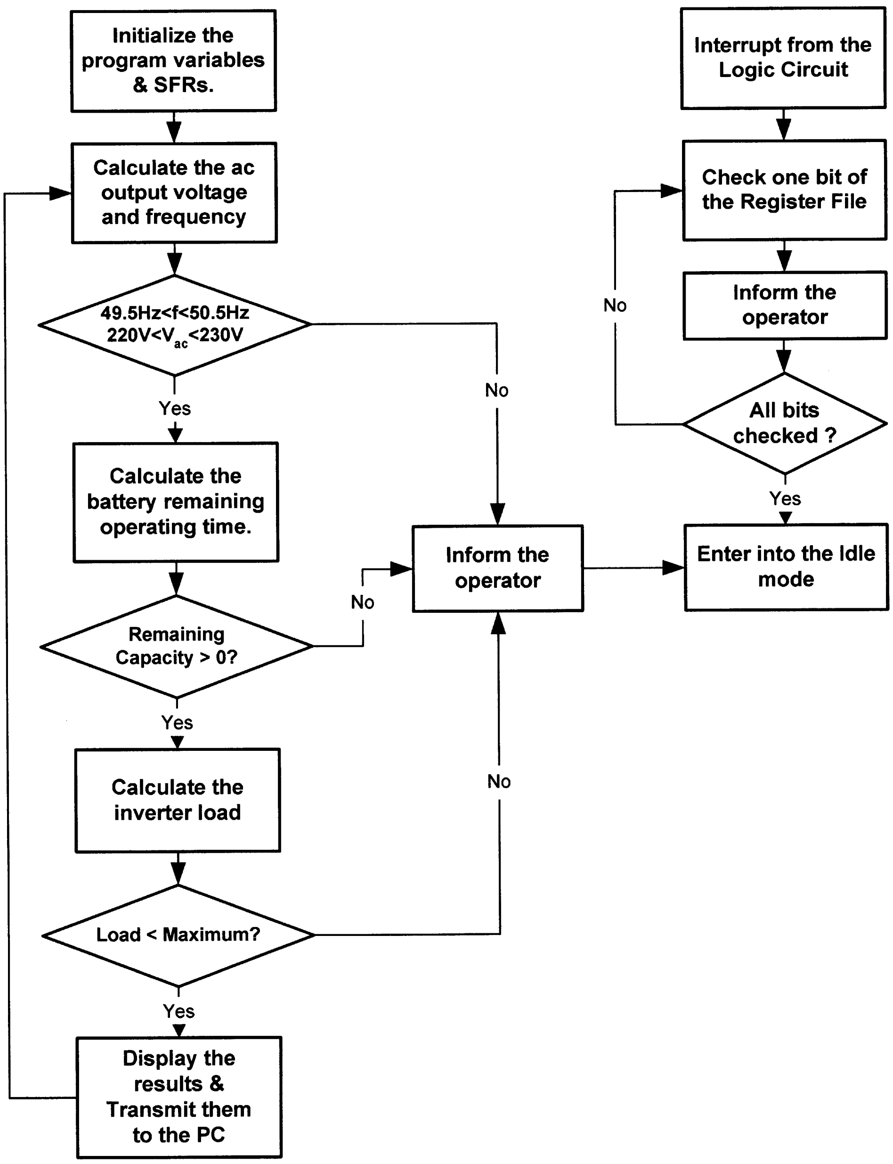


Fig. 6. Flowchart of the microcontroller program.

calculates the output voltage rms value and frequency, the inverter load as a percent of the maximum permitted load, the remaining operating time of the battery connected to the input and the ambient temperature. When the above values are calculated, the microcontroller transmits them to a LCD and through the optional RS-232 interface to a computer. In case of improper inverter operation, the microcontroller accepts an interrupt from the hardware protection unit. The normal program flow is suspended, the microcontroller checks one by one the bits of the register-set and informs the operator about the problem that suspended the inverter operation. Afterwards, the microcontroller enters into an idle mode waiting for the problem to be resolved before restarting its normal operation through reset.

The output voltage frequency is determined by sampling the corresponding A/D converter channel with a reference 3 kHz frequency and counting the number of samples between two consecutive output voltage zero-crossings. The output voltage frequency (f) is calculated by dividing the sampling frequency (f_s) with the number of samples, N, over one period:

$$f = \frac{f_s}{N} \tag{2}$$

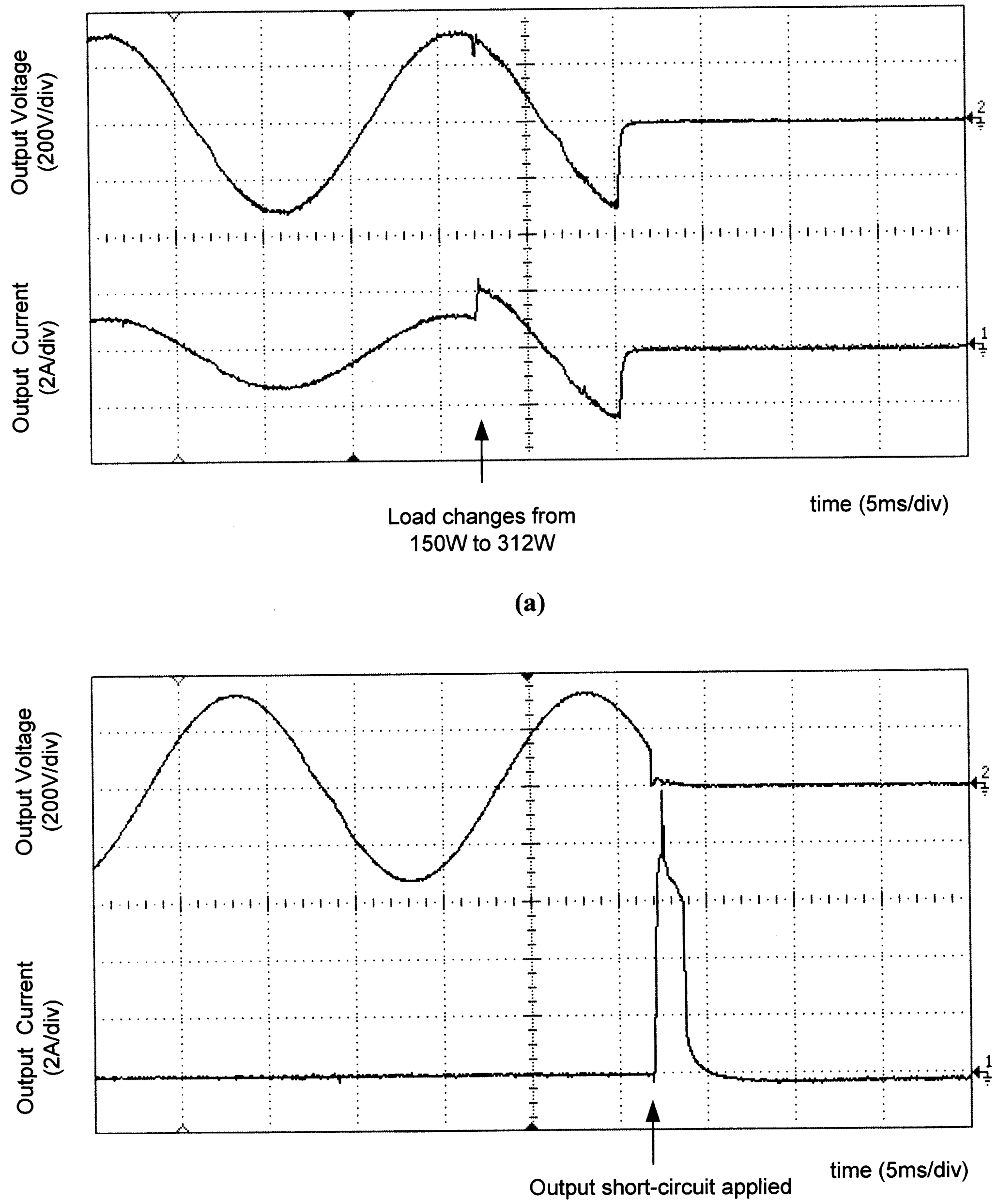


Fig. 7. The inverter output voltage and current for: (a) an output power increase from 150 to 312 W and (b) an output short-circuit condition.

The calculation of the output voltage and current rms values is done using the following relationship:

$$V_{rms} = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} V_i^2} \quad (3)$$

where V_i is the ith sample and N is the number of samples over one period, as above.

The calculation of the DC input voltage and current and of the ambient temperature is performed by taking a number of samples and applying a software low-pass filtering, in order to reduce the noise effect on the calculated values:

$$y_{calc} = \frac{\sum_{i=1}^{k} y_i}{k} \quad (4)$$

where y_{calc} is the measured value, y_i is ith sample and k is the number of samples.

The battery remaining operating time is estimated as in Ref. [18]: the battery discharging current, I_d, is multiplied by the corresponding discharging time, t_d, and the calculated charge is subtracted from the previous battery capacity, E_{d-1}, giving the battery remaining capacity, E_d :

$$E_d = E_{d-1} - I_d \cdot t_d \quad (5)$$

Initially, E_d is set equal to the nominal battery capacity in Ah. The battery remaining operating time, t_r, is estimated by the following equation:

$$t_r = \frac{E_d}{I_d} \quad (6)$$

6. Experimental results

The proposed system was tested with a laboratory-built inverter with the following specifications:

- DC input voltage 20–30 V,
- AC output voltage 220–240 V_{rms}, 50 Hz and
- Maximum output power 300 W.

Fig. 7(a) shows oscilloscope waveforms of the inverter output voltage and current for a step increase of the inverter output power from 150 to 312 W. The inverter is turned-off, when the instantaneous value of the output current exceeds 2.5 A. The inverter output voltage and current waveforms for an output short-circuit condition are depicted in Fig. 7(b). The output current reaches its peak value of 10 A in about 500 ns, which is the time required by their protection circuits to turn-off the power MOSFETs. The energy stored in the inverter inductances at that moment is dissipated through current re-circulation in the inverter flyback diodes, the power transformer and the output filter until the current drops to zero. It can be observed in Fig. 8 that the inverter is turned-off when its output voltage increases beyond the 240 V_{rms} limit. The ringing when the inverter is turned-off is caused by the output filter capacitance, the internal impedance of the inverter and the energy stored in the power transformer and the output filter inductances. The inverter is turned-off when the DC input voltage drops below 20 V, as can be observed in Fig. 9(a). In this case, the DC input voltage is not disconnected from the inverter terminals. Fig. 9(b) illustrates the inverter input and output voltage waveforms for an input overvoltage condition. When the input supply voltage exceeds 30 V, switch S in Fig. 3 is opened, in order to prevent the destruction of the inverter stages. At this time, the inverter capacitors, which are in parallel with the inverter DC input terminals, forming capacitor C_s in Fig. 3, are rapidly discharged. When their voltage reaches 20 V, the under-voltage protection circuit turns-off the inverter. Capacitor C_s is now discharged at a slower rate, since its energy is dissipated only by the control circuits.

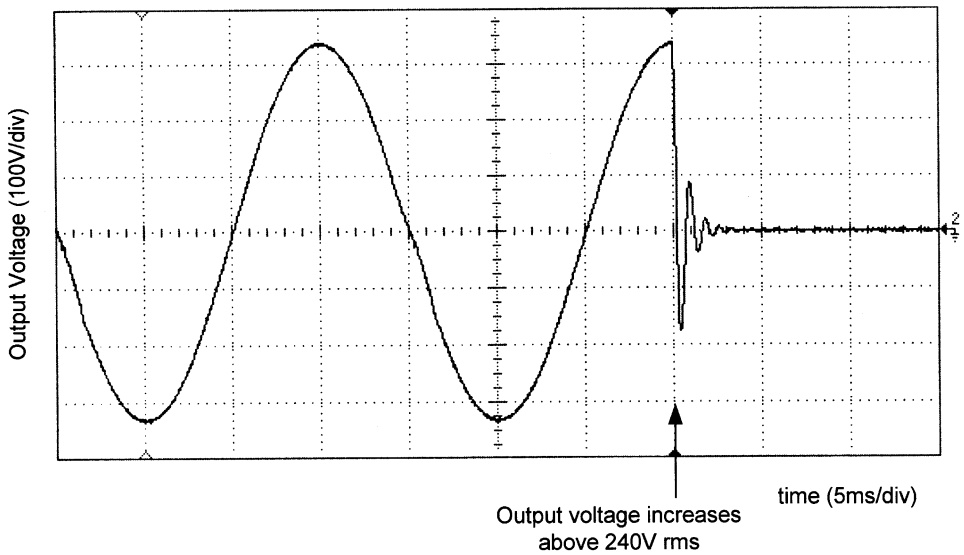


Fig. 8. The inverter output voltage when it increases above 240 V_{rms}.

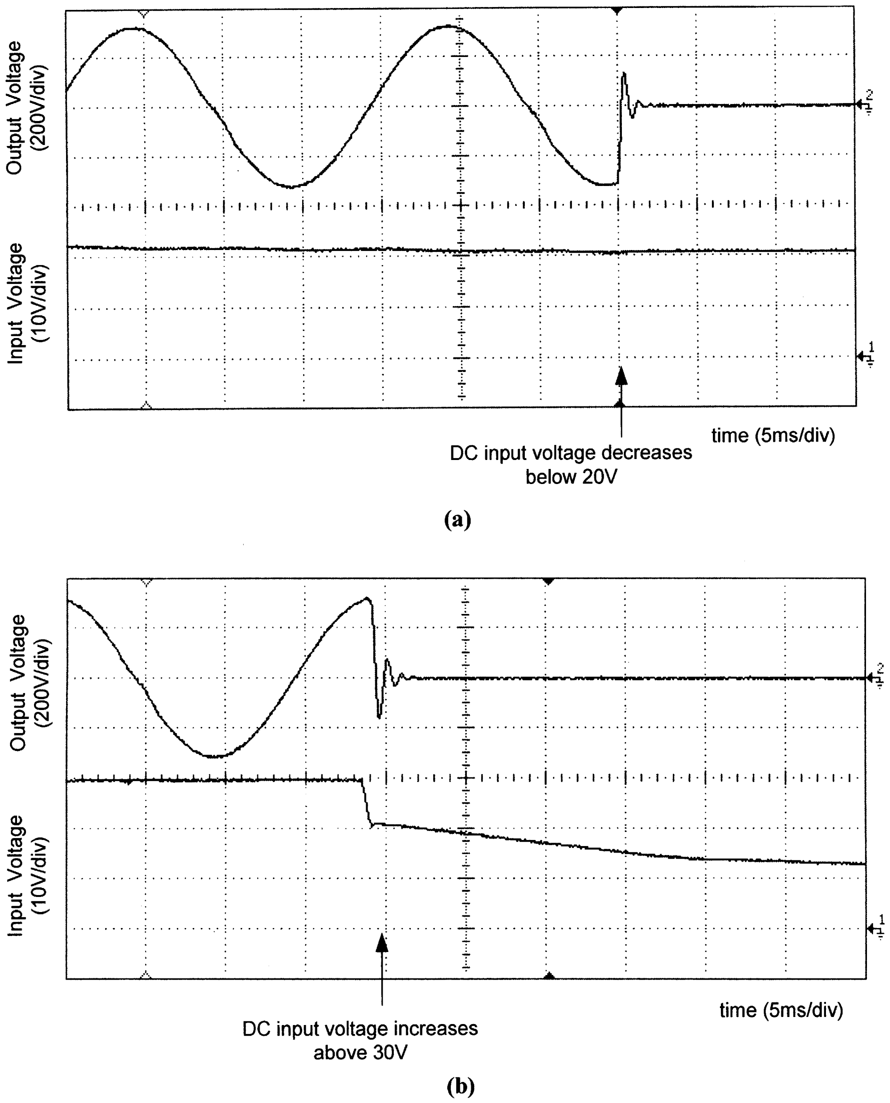


Fig. 9. The inverter input and output voltages when: (a) the DC input voltage drops below 20 V and (b) the input voltage exceeds 30 V.

Under all severe violations of specifications tested, the proposed system turned-off the inverter successfully, thus ensuring fail-safe inverter protection.

Both, the proposed system and the test inverter are laboratory-built using off-the-shelf electronic components. The cost of the proposed unit mainly consists of the microcontroller, the sensors, the LCD and the control unit ICs cost and is estimated to be approximately 30% of the above-mentioned inverter cost. But, since the cost does not increase substantially as the inverter power capability increases, its application to a higher power inverter becomes more economically efficient.

7. Conclusions

A low-cost, real-time control unit has been developed, which can effectively protect and monitor a DC/AC converter (inverter). The system is designed to assure that the inverter output voltage drops to zero (fail-safely) in case of improper operation, while the control unit malfunctions have not been investigated in this study. The system design is based on a high performance microcontroller and can be built using off-the-shelf electronic components. An experimental model of the proposed control unit has been constructed in the laboratory and was tested with an SPWM inverter. The experimental results prove that the proposed system ensures absolute inverter protection and fail-safe operation.

The proposed unit can be used to increase the reliability of any power inverter applied in AC motor drives, renewable energy systems, etc. or can be incorporated in any UPS system. In the latter case, the operations of battery charging and AC/DC converter monitoring must be included in the existing microcontroller algorithm. Advanced battery monitoring algorithms [19] and digital

PWM inverter control techniques [20] can also be incorporated in the microcontroller unit, comprising a completely integrated power supply system.

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