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(54) Title: UNIVERSAL HARDWARE/SOFTWARE FEEDBACK CONTROL FOR HIGH-FREQUENCY SIGNALS
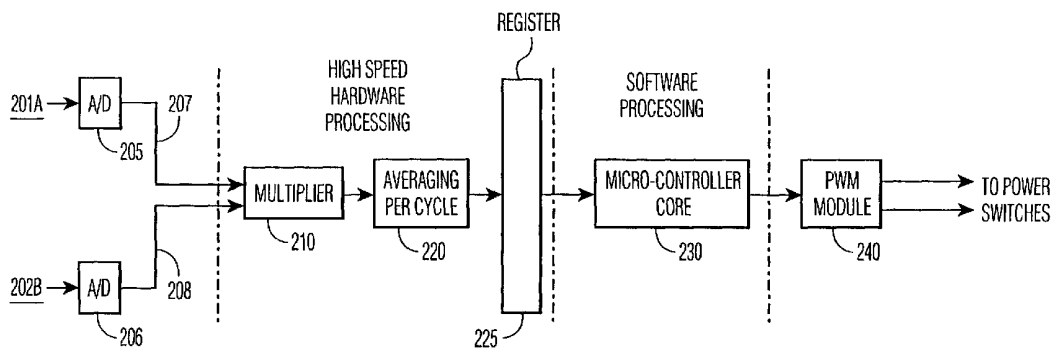
(57) Abstract: A method and apparatus for providing closed loop feedback control is presented. The method consists of a hybrid software and hardware solution to take advantage of the useful attributes of both. Analog signals output by the device are sampled at a rate sufficient to preserve all necessary high frequency information, and preprocessed at high speed in hardware. The outputs of the preprocessing stage are then operated on in software at much lower speeds. The method and apparatus allow for the complex real time processing of feedback signals in the digital domain, yet allow the cost efficiencies and programming flexibility of a standard micro-controller to be utilized.

Universal hardware/software feedback control for high-frequency signals

This invention relates generally to a method and apparatus for providing closed loop feedback control for a circuit. This invention has particular application in the feedback control of high-frequency switching mode power converters used in lighting applications.

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Future intelligent power management systems for lighting applications will require electronic ballasts with network control and communications capabilities. As well, the emerging electronic ballast must be universal. It must be able to drive different lamp types as well as operate globally, i.e., be interoperable with differing AC line voltages.

10   An electronic ballast drives a lamp with a nearly sinusoidal wave of a particular frequency. The driving pulse output by the ballast is generally a combination of one or more outputs of a switching-mode power converter, such as, e.g., a half-bridge power converter. These power-converter outputs are generally square waveforms, but before being applied to the lamp, are passed through an LC tank, resulting in near sinusoidal waveforms

15   applied to the lamp.

The output signals of switching-mode power converters used in lamp driving circuits are periodic waveforms whose frequencies are equal to the switching frequency of the converters. The width and frequency of these output signals govern the intensity, and therefore the power, delivered to the lamp. In order to properly regulate the output signals of

20   these switching-mode power converters a closed feedback loop is required. The feedback loop is used to continually communicate back to the electronic ballast the voltage across and current through the lamp so that the output voltage wave from the ballast can be continually controlled.

In a universal ballast, the control should be flexible and programmable. A

25   ballast should be able to calculate, for example, at least real lamp power, average rectified lamp current or rectified lamp voltage. Accordingly, the ideal ballast should be programmable so as to implement various control mechanisms, such as lamp current regulation, lamp voltage regulation, real-power regulation, or a combination of these control

methods. Such flexibility supports driving various lamp types, a feature which is more and more an important functionality in the ballast marketplace.

Unfortunately, current ballast control systems are either inflexible and non-universal, or programmable, but unable to provide real time control. Current feedback loops
5   in power converters are mostly implemented in analog hardware. They therefore comprise numerous discrete components such as resistors, capacitors, operational amplifiers, comparators, and analog integrated circuit controllers. Such feedback loop implementations are necessarily hard-wired, and thus not at all programmable.

The other approach taken in existing feedback power converter control for
10   electronic ballasts is the use of a low-cost microcontroller based integrated circuit which includes a low speed analog to digital converter for digitizing the analog input signals. Such a system is depicted in Fig. 1, operating on two feedback signals A 101 and B 102. These analog input signals A 101 and B 102 are generally the voltage and current signals coming from the lamp. The sampling speed of these analog lamp signals must be kept low in such an
15   approach, due to the limited processing speed of the standard micro-controller. As a result, in order to send low speed digitized signals to the microcontroller to be operated upon by a micro-processor implemented control algorithm, the bandwidth of the feedback signals must be significantly reduced. In order to achieve this reduction of bandwidth, the high frequency analog signals coming from the lamp must first be processed by analog low pass filters prior
20   to their being digitized by a low speed analog to digital converter. Such low pass filters are depicted as LPF 105 and LPF 106, respectively. Once the bandwidth has been limited by the analog filters, the low frequency signals 107 and 108, respectively, can be converted to the digital domain by the analog to digital converters 110 and 111, respectively. Once digitized at the low sampling speed, the signals are fed into a micro-controller 115, which operates upon
25   them and generates thereby control signals which are sent to the pulse width modulator 120 which drives the lamp.

There are significant problems inherent in each of the two above-described approaches. The feedback implementation in analog hardware includes several discrete components. The more components there are, the greater the cost; both in terms of actual
30   components as well as in terms of manufacture, design, compatibility, and testing considerations. Furthermore, a pure hardware analog feedback implementation will be limited to a particular application to insure stable operation. Since the processing of the analog signals that can be done is in no way programmable when using discrete analog components, the optimal feedback loop for a given application will only optimally work for

that one application. Flexibility is lost. This simply does not work for applications such as universal ballasts where the power converter needs to operate with different input voltages and must be able to drive a wide range of possible loads.

Additionally, the complexity of signal processing that can be done with discrete analog components is limited. As well, in truth, analog signal processing in control systems is fast becoming obsolete.

On the other hand, because the output signals of switching-mode power converters are periodic waveforms of frequency equal to the switching frequency of the converters, it is desirable in any optimal feedback control loop to preserve the high frequency information that is contained in these output signals. Lamp signals generally have a basic frequency equal to the switching frequency of the power converter that drives them, as well as numerous higher order harmonic frequencies contained in them. The harmonics present affect the lamp's power. The effects of higher order harmonics increase in proportion to the lamp dimming level. In other words, the lower the power level of the lamp, the more significant the contribution of higher order harmonics. This is generally the case because at low dim levels the pulse-width of the square waveform at the half-bridge output is reduced, resulting in increased harmonic content of the signal fed to the low pass filter. Furthermore, the lamp impedance increases at low dimming levels, thus affecting the roll-off of the filter, which in turn results in increased harmonic content of the of the signal directly driving the lamp.

To preserve the information contained in the higher order harmonics, a high sampling rate is necessitated. The well known Nyquist Sampling Theorem determines the sampling frequency that must be used to fully characterize continuous time signals by a sequence of discrete samples. The Nyquist theorem states that the sampling frequency must be at least twice as high as the maximum signal frequency.

If a microcontroller based integrated circuit feedback loop control implementation is desired to be used, then it is necessary to sample the output of the lamp circuit at twice the highest relevant harmonic of the maximum switching frequency. As an example, if the maximum switching frequency of the lamp is 100 KHz, and due to the required accuracy the effects of the first through fifth harmonics cannot be ignored, the following equation is operative: $f_S \geq 2 * 5 * f_{HB}$, i.e., the sampling frequency f_S must equal or exceed twice the fifth harmonic (or 10X) of the base frequency f_{HB}, which is the half-bridge switching frequency. In the above described example, where the maximum frequency of the lamp is 100 KHz, the sampling frequency must therefore be higher than 1 MHz.

On the other hand, if the maximum switching frequency is 100 KHz, and the information contained in the 16th order harmonic cannot be ignored based upon the accuracy requirements of the control algorithm, then the sampling frequency must be greater than or equal to 3.2 MHz. The standard microcontrollers generally used in state of the art

5   microcontroller based feedback control loops, such as, for example, the Intel 80C51, simply cannot process samples at such a high rate.

As a result of the foregoing discussion, clearly a significant need exists in the art for a feedback control loop implementation for an electric lamp which can provide both the programmable flexibility and real time complex signal processing capability of a software

10   solution operating on digitized signals, with the immediacy and speed that can only be currently achieved using a dedicated analog hardware implementation.

The above-described shortfalls of the prior art are overcome in accordance with the teachings of the present invention which relates to an apparatus and method for providing feedback loop control for a circuit in real time by means of a hybrid software and

15   hardware solution. In a preferred embodiment, this circuit is used in a digital electronic ballast controlling electric lighting, where a closed feedback loop is utilized to control a high frequency power converter. While such a power converter is frequently a half-bridge converter used with fluorescent lamps, the invention can easily be expanded to a full-bridge power converter circuit used for controlling HID lamps. In either case the driving output is an

20   AC pulse train.

The feedback signals running from the circuit output to the controller are preprocessed in specialized hardware, and then output to a processor. The processor operates upon the signals input to it according to a control algorithm implemented in software.

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Embodiments of the invention will be explained in more detail making use of a drawing. In the drawing

Fig. 1 depicts a state of the art microcontroller based feedback loop implementation;

30   Fig. 2 shows an exemplary circuit implementing the present invention; and

Fig. 3 depicts plots of amplitude versus time for various input, intermediate and output signals generated according to the method of the present invention.

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The preferred embodiment of the invention will now be described with reference to Figures 2 and 3. For purposes of illustration the preferred embodiment will be described as having a control algorithm which operates upon lamp power. There are various types of control algorithms available which can provide adequate and accurate feedback loop

5   control to regulate the output signals of switching-mode power converters, and they can, for example, be voltage based, current based, power based or some combination of the above. As well, other circuit parameters can be the operand(s) of the control algorithm. For purposes of this description of the preferred embodiment, with reference to Figure 2, the input analog signals A 201 and B 202, respectively, refer to the voltage and current signals coming from

10   the lamp.

The analog feedback signals A 201 and B 202 coming from the lamp are sampled and thereby digitized by passing them through analog to digital converters 205 and 206, respectively. In the method and apparatus of the present invention the sampling rate used in these analog to digital converters is programmable. Thus, depending on the accuracy

15   requirements of the lamp, the maximum switching frequency used by the power converter in the electronic ballast, and the harmonics of such maximum switching frequency which must be considered to comply with the required accuracy requirements of the control algorithm, a sampling rate can be user calculated.

The output of the analog to digital converters 205 and 206, being the sequence

20   of quantized samples of the original analog signals, is fed into a multiplier unit 210. The multiplier, in the embodiment described, simply multiplies the voltage signal with the current signal to generate the actual power in the lamp as a function of time. As an example, if the analog signals are sampled using an 8 bit sample, the maximum switching frequency of the power converter driving the lamp is 100 KHz, and the effects of the 16th harmonic of the

25   switching frequency must be taken into account given the accuracy required, the sampling ratio will need to be set to 32 times the base frequency or result in a sampling frequency of 3.2 MHz, and the incoming data stream will be 25.6 Mbits/sec. This data stream must undergo 8 bit multiplications in real time, which is obviously beyond the ability of standard low-cost microcontrollers. For this reason the high speed multiplication is done in dedicated

30   DSP hardware, i.e., the multiplier 210.

Because the real power is calculated by the high speed digital signal processing hardware, the multiplier 210 simply multiplies the sampled voltage and sampled current signals and produces a multiplier output consisting of a sequence of digital samples as is shown in the third plot of Fig. 3, labeled "MULTIPLIER OUTPUT" 303. The multiplier

output consists of a sequence of digital samples propogating at the same sampling rate as the digitized signals 207 and 208 which were the respective outputs of the analog to digital converters 205 and 206. Because this data rate, as above, is much higher than the standard low-cost microcontroller, such as the Intel 8051 and the like, can process, before the product

5   (of voltage and current) data stream, being the digitized instantaneous power in the lamp, can be processed by the microcontroller 230, it must be slowed down. This is accomplished by averaging, done by the averager 220, and the averaged output is ultimately input to the microcontroller 230. The microcontroller 230 implements the control algorithm which, in this example, operates on the lamp power. The output of the averaging module is shown, with

10   reference to Figure 3, as the bottom plot, entitled "AVERAGING OUTPUT". As can readily be seen, the sample rate of the averager output is much less than the original sampling frequency utilized in the analog to digital converters 205 and 206. Obviously, the averaging output sample rate is programmable and can be varied as necessary or desired to interface with the software implemented control algorithm for real time control. In Figure 3, the

15   averager output 304 was arrived at by using a down sampling ratio of 16, so as to return to the original switching frequency of the lamp, and is therefore equal to the frequency of the original analog signals A 301 and B 302.

       The output of the averaging module 220 is next fed into a register 225, which is accessed and read from by the microcontroller 230. The microcontroller 230, operating at

20   the lower sample rate on the averaging output 304 (as shown in Figure 3) can thus be a commonly available, low-cost, low-power microcontroller. The microcontroller operates on its input data stream according to the control algorithm, and sets the poles and zeros of the feedback loop. Ultimately, the microcontroller output is taken as input by the Pulse Width Modulation module 240, which regulates the width and frequency of the voltage pulses

25   delivered to the lamp.

       While the foregoing describes the preferred embodiment of the invention, it is understood by those of skill in the art that various modifications and variations may be utilized, such as, for example, using the invention in circuits that have any waveform as driving outputs, both ac and dc, and the extension of the circuit of the preferred embodiment

30   to any number of output signals, each with one or more hardware and software data sources. Additionally, given this flexibility, the control algorithm can operate on any number of inputs, and calculate a wide range of intermediate signals to be fed to a processor implementing a control algorithm. Such modifications are intended to be covered by the following claims.

CLAIMS:

1.   A method of providing feedback control to a device comprising:

preprocessing high frequency feedback signals (201,202) in hardware (210,220); and

operating upon the preprocessed signals in software(230).

5   2.   The method of claim 1, where the preprocessing comprises user defined digital

signal processing operations (210,220).

3.   The method of claim 2, where the digital signal processing operations are done

in real time.

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4.   The method of claim 3, where the digital signal processing operations

comprise analog to digital conversion (205,206) utilizing a sampling rate sufficient to

preserve all high frequency information.

15   5.   The method of claim 4, where operating upon the preprocessed signals in

software (230) comprises implementation of a user defined control algorithm.

6.   The method of claim 5, where the control algorithm can be run on a standard

micro-controller (230).

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7.   The method of claim 6, where the preprocessing further comprises:

multiplying the feedback signals (210); and

averaging the product thus obtained (220).

25   8.   The method of claim 7, where the device is a ballast circuit for operating a

lamp.

9.   The method of claim 8, where the feedback signals (201,202) comprise the

voltage across, and current through, the lamp.

10.   Apparatus for providing feedback control comprising:

hardware for preprocessing of feedback signals (210,220); and

a microprocessor (230) for operating upon the preprocessed signals by implementing a

5   software control algorithm.

11.   The apparatus of claim 10, wherein the hardware comprises:

an analog to digital converter (205,206); and

high speed digital processing circuitry (210,220).

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12.   The apparatus of claim 11, wherein the high-speed digital processing circuitry

further comprises:

a multiplier (210); and

an averaging module (220).

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13.   The apparatus of claim 12, further comprising memory elements (225).

14.   The apparatus of claim 13, wherein the rate of samples processed by the high

speed digital processing circuitry exceeds the maximum data processing rate of the

20   microprocessor.

15.   The apparatus of claim 14, where the feedback control is provided to a lighting

device.

25   16.   The apparatus of claim 15, where the feedback signals comprise at least one
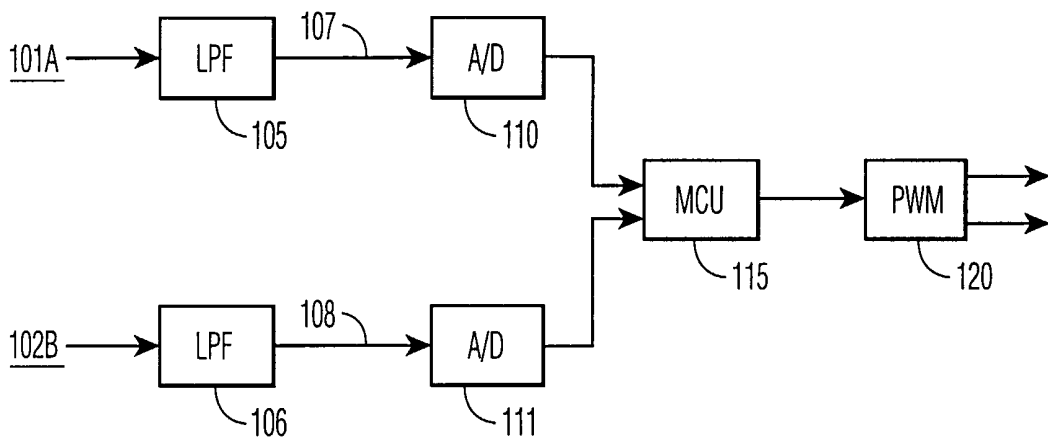
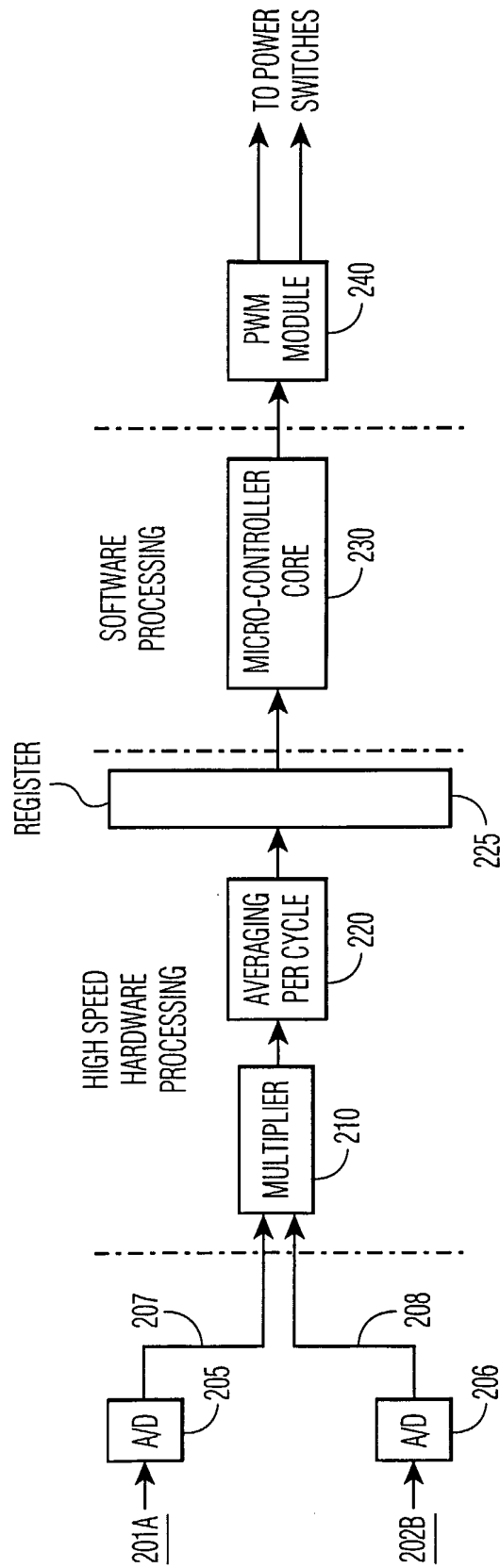of:

the lamp voltage (201); and
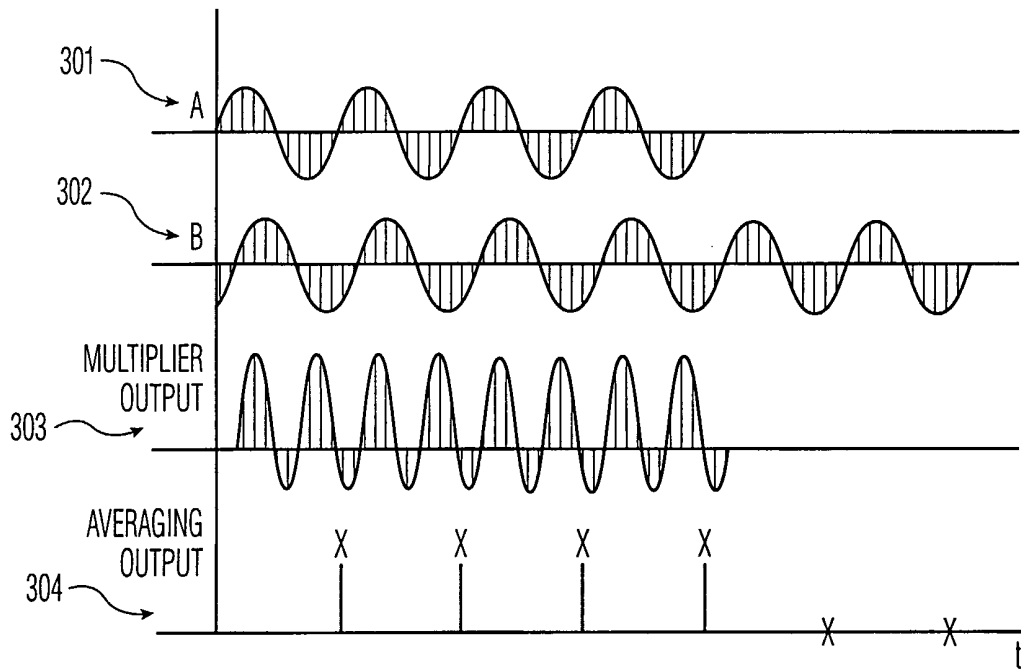
the lamp current (202).

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FIG. 1

FIG. 2

FIG. 3

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   H05B41/392   H05B41/38   G05B13/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   H05B   G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	US 5 862 507 A (LEE ANSON ET AL) 19 January 1999 (1999-01-19) column 5, line 20 -column 9, line 13; figures 1-3	1-6,10, 11
X	US 5 806 055 A (ZINDA JR KENNETH L) 8 September 1998 (1998-09-08) column 2, line 28 -column 8, line 56; figures 1,2,7	1,10
X	US 5 345 188 A (OWEN JEFFREY R) 6 September 1994 (1994-09-06) abstract; figures 1-3	1-5, 10-13

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	X	Further documents are listed in the continuation of box C.		X	Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
25 July 2002	01/08/2002

Name and mailing address of the ISA	Authorized officer
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Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
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