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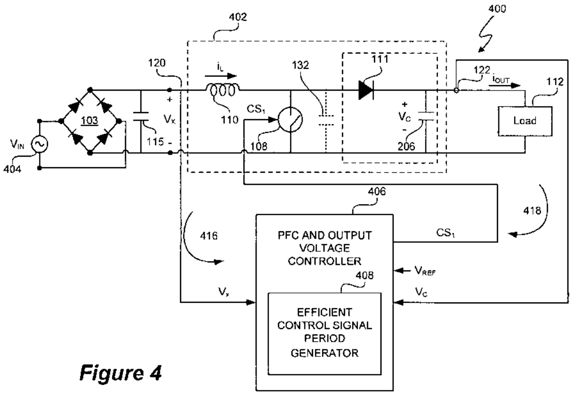

Figure 4

(57) **Abstract:** A power control system includes a switching power converter (402) and a controller (406), and the controller (406) responds to a time-varying voltage source signal (Vx) by generating a switch control signal (CSl) having a period that varies in accordance with at least one of the following: (i) the period of the switch control signal trends inversely to estimated power delivered to a load (112) coupled to the switching power converter (402), (ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal (Vx), and (iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal (Vx). In at least one embodiment, the controller (406) achieves an efficient correlation between the switching period with associated switching losses and the instantaneous power transferred to the switching power converter while providing power factor correction.

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SWITCHING POWER CONVERTER WITH EFFICIENT SWITCHING CONTROL SIGNAL PERIOD GENERATION

John L. Melanson

Cross-reference to Related Application

(1) This application claims the benefit under 35 U.S.C. § 119(e) and 37 C.F.R. § 1.78 of U.S. Provisional Application No. 60/915,547, filed on May 2, 2007 and entitled “Power Factor Correction (PFC) Controller Apparatuses and Methods”.

BACKGROUND OF THE INVENTION

Field of the Invention

(2) The present invention relates in general to the field of electronics, and more specifically to a system and method for voltage conversion using a switching power converter with efficient switching control signal period generation.

DESCRIPTION OF THE RELATED ART

(3) Many devices utilize electrical power to operate. Power is initially supplied by a power source, such as a public utility company, and power sources generally provide a steady state input voltage. However, the voltage levels utilized by various devices may differ from the steady state input voltage provided by the power source. For example, light emitting diode (LED) based lighting systems, typically operate from voltage levels that differ from voltage level supplied by a public utility company. To accommodate the difference between the voltage from the power source and the voltage utilized by the device, power converters are connected between the power source and the device to convert a supply voltage level from an alternating current (AC) power source to, for example, another AC power source having a voltage level different than the supply voltage level. Power converters can also convert AC power into direct (DC) power and DC power into AC power.

(4) Switching power converters represent one example of a type of power converter. A switching power converter utilizes switching and energy storage technology to

convert an input voltage into an output voltage suitable for use by a particular device connected to the switching power converter.

(5) Figure 1 depicts a power control system 100, which includes a switching power converter 102. Voltage source 101 supplies an AC input “mains” voltage V_{mains} to a full, diode bridge rectifier 103. The voltage source 101 is, for example, a public utility, and the AC mains voltage V_{mains} is, for example, a 60 Hz/120 V mains voltage in the United States of America or a 50 Hz/230 V mains voltage in Europe. The rectifier 103 rectifies the input mains voltage V_{mains}. The rectifier 103 rectifies the input mains voltage V_{mains} and supplies a rectified, time-varying, primary supply voltage V_X to the switching power converter. The switching power converter 102 provides approximately constant voltage power to load 112 while maintaining a resistive input characteristic to voltage source 101. Providing approximately constant voltage power to load 112 while maintaining an approximately resistive input characteristic to voltage source 101 is referred to as power factor correction (PFC). Thus, a power factor corrected switching power converter 102 is controlled so that an input current i_L to the switching power converter 102 varies in approximate proportion to the AC mains voltage V_{mains}.

(6) PFC and output voltage controller 114 controls the conductivity of PFC switch 108 so as to provide power factor correction and to regulate the output voltage V_C of switching power converter 102. The PFC and output voltage controller 114 attempts to control the inductor current i_L so that the average inductor current i_L is linearly and directly proportional to the primary supply voltage V_X. A proportionality constant relates the inductor current i_L to the primary supply voltage V_X, and the proportionality constant is adjusted to regulate the voltage to load 112. The PFC and output voltage controller 114 supplies a pulse width modulated (PWM) switch control signal CS_0 to control the conductivity of switch 108. In at least one embodiment, switch 108 is a field effect transistor (FET), and switch control signal CS_0 is the gate voltage of switch 108. The values of the pulse width and duty cycle of switch control signal CS_0 depend on at least two signals, namely, the primary supply voltage V_X and the capacitor voltage/output voltage V_C. Output voltage V_C is also commonly referred to as a “link voltage”. Current control loop 119 provides current i_{RTN} to PFC

and output voltage controller 114 to allow PFC and output voltage controller 114 to adjust an average i_L current 210 (Figure 2) to equal a target i_L current 208 (Figure 2).

(7) Capacitor 106 supplies stored energy to load 112 when diode 111 is reverse biased and when the primary supply voltage V_X is below the RMS value of the input mains. The value of capacitor 106 is a matter of design choice and, in at least one embodiment, is sufficiently large so as to maintain a substantially constant output voltage V_C, as established by a PFC and output voltage controller 114. A typical value for capacitor 106, when used with a 400 V output voltage V_C, is 1 microfarad per watt of maximum output power supplied via switching power converter 102. The output voltage V_C remains at a substantially constant target value during constant load conditions with ripple at the frequency of primary supply voltage V_X. However, as load conditions change, the output voltage V_C changes. The PFC and output voltage controller 114 responds to the changes in voltage V_C by adjusting the switch control signal CS_0 to return the output voltage V_C to the target value. In at least one embodiment, the PFC and output voltage controller 114 includes a small capacitor 115 to filter any high frequency signals from the primary supply voltage V_X.

(8) The switching power converter 102 incurs switching losses each time switch 108 switches between nonconductive and conductive states due to parasitic impedances. The parasitic impedances include a parasitic capacitance 132 across switch 108. During each period TT of switching switch control signal CS_0, energy is used to, for example, charge parasitic capacitance 132. Thus, switching power converter 102 incurs switching losses during each period TT of switch control signal CS_0.

(9) PFC and output voltage controller 114 controls switching power converter 102 so that a desired amount of power is transferred to capacitor 106. The desired amount of power depends upon the voltage and current requirements of load 112. An input voltage control loop 116 provides a sample of primary supply voltage V_X to PFC and output voltage controller 114. PFC and output voltage controller 114 determines a difference between a reference voltage V_{REF}, which indicates a target voltage for output voltage V_C, and the actual output voltage V_C sensed from node 122 and received as feedback from voltage loop 118. The PFC and output voltage controller 114 generally utilizes technology, such as proportional integral (PI) compensation control, to respond to differences in the output voltage V_C relative to the reference

voltage V_{REF}. The PFC and output voltage controller 114 processes the differences to smoothly adjust the output voltage V_C to avoid causing rapid fluctuations in the output voltage V_C in response to small error signals. The PFC and output voltage controller 114 generates a pulse width modulated switch control signal CS_0 that drives switch 108. Prodić, *Compensator Design and Stability Assessment for Fast Voltage Loops of Power Factor Correction Rectifiers*, IEEE Transactions on Power Electronics, Vol. 12, No. 5, Sept. 1007, pp. 1719-1729 (referred to herein as "Prodić"), describes an example of PFC and output voltage controller 114.

(10) Figures 2 and 3 depict respective switching control strategies utilized by typical switching power converters, such as switching power converter 102, to convert the input voltage V_X into a power factor corrected output voltage V_C. Figure 2 depicts a transition switching strategy, and Figure 3 depicts a constant period switching strategy. Referring to Figures 1 and 2, PFC and output voltage controller 114 controls the conductivity of PFC switch 108. The primary supply voltage V_X 202 is, in at least one embodiment, a rectified sine wave. To regulate the amount of power transferred and maintain a power factor close to one, PFC and output voltage controller 114 varies the period TT of switch control signal CS_0 so that the inductor current i_L (also referred to as the 'input current') tracks changes in primary supply voltage V_X and holds the output voltage V_C constant. The transition switching strategy 204 illustrates that, as the primary supply voltage V_X increases, PFC and output voltage controller 114 increases the period TT of switch control signal CS_0. As the primary supply voltage V_X decreases, PFC and output voltage controller 114 decreases the period of switch control signal CS_0. In one embodiment of transition switching strategy 204, the pulse width time T1 is approximately constant.

(11) Time T2 represents the flyback time of inductor 110 that occurs when switch 108 is nonconductive and the diode 111 is conductive. In at least one embodiment, the value of inductor 110 is a matter of design choice. In at least one embodiment, the value of inductor 110 is chosen to store sufficient power transferred from voltage source 101 when switch 108 conducts in order to transfer power to capacitor 106 when switch 108 is non-conductive to maintain a desired output voltage V_C. For the transition switching strategy 204, the pulse width time T1 plus the flyback time T2 equals the period TT of switch control signal CS_0.

(12) The inductor current i_L waveform 206 depicts the general behavior of inductor current i_L over time relative to the primary supply voltage V_X. The inductor current i_L ramps 'up' during pulse width T1 when the switch 108 conducts, i.e. is "ON". The inductor current i_L ramps down during flyback time T2 when switch 108 is nonconductive, i.e. is "OFF", and supplies inductor current i_L through diode 111 to recharge capacitor 106. Discontinuous conduction mode (DCM) occurs when the inductor current i_L reaches 0 during the period TT of switch control signal CS_0. Continuous conduction mode (CCM) occurs when the inductor current i_L is greater than 0 during the entire period TT. Transition switching strategy 204 operates switching power converter 102 at the boundary of DCM and CCM by beginning each period of switch control signal CS_0 when the inductor current i_L just equals 0. The frequency 1/TT of switch control signal CS_0 is, for example, between 20 kHz and 130 kHz. The period TT of switch control signal CS_0 and, thus, the duration of each cycle of inductor i_L depicted in inductor current i_L waveform 206 is exaggerated for visual clarity. Transition switching strategy 204 operates the switch 108 at high frequencies when little power is transferred from voltage source 101, such as near the zero crossing 212 of the mains voltage V_{mains} and at light load, i.e. when the power demand of load 112 is light.

(13) The PFC and output voltage controller 114 sets a target current 208 that tracks the primary supply voltage V_X. When the inductor current i_L reaches the target current 208 during the pulse width T1, the switch control signal CS_0 opens switch 108, and inductor current i_L decreases to zero during flyback time T2. The average current 210 represents the average inductor current i_L. The average inductor current i_L tracks the primary supply voltage V_X, thus, providing power factor correction.

(14) Referring to Figure 3, the constant period switching strategy 302 maintains a constant period TT of switch control signal CS_0 and varies the pulse width T1 of switch control signal CS_0 to control inductor current i_L. As the primary supply voltage V_X increases from 0 to line peak, PFC and output voltage controller 114 decreases the pulse width T1 of switch control signal CS_0. Constant period switching strategy 302 operates switching power converter 102 in DCM so that the flyback time T2 plus the pulse width T1 is less than or equal to the period TT of switch control signal CS_0. Inductor current i_L waveform 304 depicts the effects of the constant

period switching strategy 302 on the inductor current i_L relative to the primary supply voltage V_X. As with the transition switching strategy 204, for the constant period switching strategy 302, the PFC and output voltage controller 114 sets a target current 208 that tracks the primary supply voltage V_X. For constant period strategy 302, $TT \geq (T1+T2)$, so switching power converter 102 operates in DCM.

(15) PFC and output voltage controller 114 updates the switch control signal CS_0 at a frequency much greater than the frequency of input voltage V_X. The frequency of input voltage V_X is generally 50-60 Hz. The frequency 1/TT of switch control signal CS_0 is, for example, between 10 kHz and 130 kHz. Frequencies at or above 20 kHz avoid audio frequencies and frequencies at or below 130 kHz avoids significant switching inefficiencies.

(16) The constant period switching strategy 302 is not efficient in terms of switching losses versus power delivered to load 112. The transition switching strategy 204 is even less efficient than the constant period switching strategy 302.

SUMMARY OF THE INVENTION

(17) In one embodiment of the present invention, a system includes a controller to generate a switch control signal to control conductivity of a switch included in a switching power converter. Controlling conductivity of the switch causes an input current to the switching power converter to vary in approximate proportion to a time varying voltage source signal supplied to the switching power converter. The controller includes a period generator to determine a period of the switch control signal so that the period of the switch control signal varies in accordance with at least one of:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;
(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the time-varying voltage source signal; and
(iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal; and

(18) The controller also includes a pulse width generator to determine a pulse width of the switch control signal in response to at least one of: : (i) the determined period

of the switch control signal, (ii) the instantaneous voltage levels of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter.

(19) In another embodiment of the present invention, a method includes generating a switch control signal to control conductivity of a switch included in a switching power converter. Controlling conductivity of the switch causes an input current to the switching power converter to vary in approximate proportion to a time varying voltage source signal supplied to the switching power converter. The method further includes determining a period of the switch control signal so that the period of the switch control signal varies in accordance with at least one of:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;
(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal; and
(iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal;

(20) The method also includes determining a pulse width of the switch control signal in response to at least one of: (i) the determined period of the switch control signal, (ii) a voltage level of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter. The method further includes providing the switch control signal to the switching power converter.

(21) In another embodiment of the present invention, an apparatus includes means for generating a switch control signal to control conductivity of a switch included in a switching power converter. Controlling conductivity of the switch causes an input current to the switching power converter to vary in approximate proportion to a time varying voltage source signal supplied to the switching power converter. The apparatus further comprises means for determining a period of the switch control signal so that the period of the switch control signal varies in accordance with at least one of:

(i) the period of the switch control signal trends inversely to instantaneous power transferred to the switching power converter;

(ii) the period of the switch control signal trends inversely to voltage level changes of the voltage source signal; and

(iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal; and

(22) The apparatus also includes means for determining a pulse width of the switch control signal in response to at least one of: (i) the determined period of the switch control signal, (ii) a voltage level of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter.

BRIEF DESCRIPTION OF THE DRAWINGS

(23) The present invention may be better understood, and its numerous objects, features and advantages made apparent to those skilled in the art by referencing the accompanying drawings. The use of the same reference number throughout the several figures designates a like or similar element.

(24) Figure 1 (labeled prior art) depicts a power control system, which includes a switching power converter.

(25) Figure 2 (labeled prior art) depicts a transition switching control strategy and the effect of the transition switching control strategy on an inductor current of the switching power converter of Figure 1.

(26) Figure 3 (labeled prior art) depicts a constant period switching control strategy and the effect of the constant period switching control strategy on an inductor current of the switching power converter of Figure 1.

(27) Figure 4 depicts a power control system having a switching power converter and a control signal period-power transfer correlation strategy module.

(28) Figure 5 depicts a collection of correlated waveforms that depict a correlation between a primary supply voltage, an inductor current, and transferred power in the power control system of Figure 4.

(29) Figure 6 depicts an efficient period-instantaneous primary supply voltage V_X correlation strategy.

(30) Figure 7 depicts correlated waveforms between an inductor current and switch control signal of the power control system of Figure 4.

(31) Figure 8 depicts a power factor correction (PFC) and output voltage controller of the power control system of Figure 4.

(32) Figures 9-13 depict efficient period-instantaneous primary supply voltage V_X correlation strategies.

(33) Figure 14 depicts a nonlinear delta-sigma modulator.

(34) Figure 15 depicts a proportional integrator.

(35) Figures 16 and 17 depict respective root mean square value generators.

(36) Figure 18 depicts another embodiment of a PFC and output voltage controller of the power control system of Figure 4.

(37) Figures 19-21 depict efficient period-power transfer-instantaneous primary supply voltage correlation strategies for multiple primary supply RMS voltages and multiple power transfer percentages.

DETAILED DESCRIPTION

(38) A power control system includes a switching power converter and a controller, and the controller responds to a time-varying voltage source signal by generating a switch control signal having a period that varies in accordance with at least one of: (i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter, (ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal, and (iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal. The power control system also includes a pulse width generator to determine a pulse width of the switch control signal in response to at least one of (i) the determined period of the switch control signal, (ii) the instantaneous voltage levels of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter. Thus, the period can be determined in accordance with a one-way function, two-way function, or three-way function of the variables: (i) estimated power delivered to a load coupled to the switching power converter, (ii) instantaneous voltage levels of the

voltage source signal, and (iii) line voltage level of the time-varying voltage source signal (collectively referred to as the "Period Determination Variables"). A "one-way function" indicates that one of the Period Determination Variables (i), (ii), or (iii) is used to determine the switch control signal period. A "two-way function" indicates that any two of the Period Determination Variables (i), (ii), or (iii) are used to determine the switch control signal period. A "three-way function" indicates that all three of the Period Determination Variables (i), (ii), or (iii) are used to determine the switch control signal period.

(39) For power supplies having a voltage source signal that approximates a sine wave, the switching power converter transfers 80% of the power from the voltage source to the load when a phase angle of the voltage source signal is between 45° and 135°. Switching losses in the switching power converter generally increase as switching periods decrease, or, in other words, switching losses in the switching power converter generally increase as switching frequencies increase. By varying the period of the switch control signal so that the period trends in accordance with the one-way function, two-way function, or three-way function of the Period Determination Variables, in at least one embodiment, the controller achieves an efficient correlation between the switching period with associated switching losses and the Period Determination Variable(s) while providing power factor correction (PFC).

(40) Figure 4 depicts a power control system 400 having a switching power converter 402 and an efficient control signal period generator 408. In at least one embodiment, switching power converter 402 is configured in the same manner as switching power converter 102. Rectifier 103 rectifies the input voltage V_{IN} supplied by voltage source 404 to generate time varying, primary supply voltage V_X. In at least one embodiment, voltage source 404 is identical to voltage source 101, and input voltage V_{IN} is identical to the mains voltage V_{mains}. Power control system 400 also includes PFC and output voltage controller 406. PFC and output voltage controller 406 generates switch control signal CS_1 using feedback signals representing the primary supply voltage V_X and output voltage V_C. PFC and output voltage controller 406 includes the efficient control signal period generator 408 to efficiently correlate a

period TT of switch control signal CS_1 with the Period Determination Variables to, for example, increase the efficiency of power control system 400.

(41) In at least one embodiment, the Period Determination Variables are the: (i) estimated power delivered to load 112, (ii) instantaneous voltage levels of primary supply voltage V_X, and (iii) line voltage level of primary supply voltage V_X. In at least one embodiment, the estimated power delivered to load 112 is estimated by multiplying the average output voltage V_C obtained via voltage control loop 418 and the average output current i_{OUT} of switching power converter 402. In at least one embodiment, the estimated power delivered to load 112 is a value “K” determined by the load power demand estimator 803 of Figure 8. In at least one embodiment, the instantaneous voltage levels of primary supply voltage V_X represent a values of primary supply voltage V_X sampled via voltage loop 416 at a rate approximately equal to 1/TT, where 1/TT represents the frequency of switch control signal CS_1. The term “instantaneous” includes delays, such as any transmission and processing delays, in obtaining the sampled value of primary supply voltage V_X. In at least one embodiment, the line voltage level of primary supply voltage V_X represents a measure of the primary supply voltage V_X for at least one period of primary supply voltage V_X. For example, in at least one embodiment, the line voltage level is the root mean square (RMS) of primary supply voltage V_X, a peak of primary supply RMS voltage V_{X_RMS}, or an average of primary supply voltage V_X. For example, the line voltage in the United States of America is nominally 120 Vrms, and the line voltage in Europe is nominally 230 Vrms, where “Vrms” represents an RMS voltage. In general, the line voltage level and the load power demand will be updated at a rate of 50-240 Hz, and the instantaneous voltage will be updated at the switching frequency of switch 108, i.e. the frequency of switch control signal CS_1.

(42) In at least one embodiment, the efficient control signal period generator 408 includes a control signal period strategy that allows the PFC and output voltage controller 406 to generate a period TT of the switch control signal CS_1 that varies in accordance with at least one of the Period Determination Variables.

(43) Figure 5 depicts a collection of correlated waveforms 500 that depict a correlation between the primary supply voltage V_X 502, the inductor current i_L 504, and power 506 transferred from voltage source 404 to switching power converter 402.

One-half of the period of primary supply voltage V_X occurs between phase angles 0°-45° plus phase angles 135°-180°. The RMS voltage of primary supply voltage V_X equals the voltage at phase angles 45° and 135°. Thus, primary supply voltage V_X is greater than the primary supply RMS voltage V_{X_RMS} for a time equal to half the period TT of primary supply voltage V_X and less than the primary supply RMS voltage V_{X_RMS} for a time equal to half the period of TT. The peak voltage of a sine wave primary supply voltage V_X is $\sqrt{2} \cdot V_{X\_RMS}$. To provide power factor correction, PFC and output voltage controller 406 generates switch control signal CS_1 so that the average inductor current i_L 508 tracks the primary supply voltage V_X. Power 506 transferred from voltage source 404 to switching power converter 402 equals $V_X \cdot i_L$. Eighty percent of the power 506 is transferred to switching power converter 402 when primary supply voltage V_X is greater than primary supply RMS voltage V_{X_RMS}, and twenty percent of the power 506 is transferred when primary supply voltage V_X is less than primary supply RMS voltage V_{X_RMS}. In other words, 80% of the power 506 is transferred when primary supply voltage V_X is between phase angles 45° and 135°, and 20% of the power 506 is transferred in the troughs of primary supply voltage V_X. In at least one embodiment, the troughs of primary supply voltage V_X are below primary supply RMS voltage V_{X_RMS} and, for a sine wave, are between phase angles 0°-45° and between phase angles 135°-180°.

(44) Switching power converter 402 also incurs switching losses each time switch 108 switches between nonconductive and conductive states due to parasitic impedances. During each period TT of switching switch control signal CS_1, power is used to, for example, charge parasitic capacitance 132. Switching power converter 402 incurs switching losses during each period TT of switch control signal CS_1. Thus, the higher the frequency of controls signal CS_1, the higher the switching loss.

(45) Referring to Figures 1-5, with respect to the conventional transition switching strategy 204, the frequency of switch control signal CS_0 is highest between phase angles 0°-45° and phase angles 135°-180°. Thus, the conventional transition switching strategy 204 incurs the greatest switching loss during the time of the lowest amount of power transfer from voltage source 101 to switching power converter 102. In at least one embodiment, more than half (>50%) of the switching loss associated with the conventional transition switching strategy 204 occurs during the transfer of

20% of the power from voltage source 101 to switching power converter 102. The constant period switching strategy 302 is somewhat more efficient because only approximately 50% of the switching loss associated with the conventional transition switching strategy 204 occurs during the transfer of 20% of the power from voltage source 101 to switching power converter 102.

(46) In at least one embodiment, the efficient control signal period generator 408 allows the PFC and output voltage controller 406 to improve the efficiency of power control system 400 by increasing the period TT of switch control signal CS_1, or in other words decreasing the switching rate of switch 108, during times of low power transfer to load 112, low instantaneous primary supply voltage V_X, and/or higher primary supply RMS voltage V_{X_RMS}. Table 1 sets forth an exemplary switching loss to power transfer ratio comparison: The actual power savings and optimum switch control signal CS_1 period TT generation strategy depend on power components of power control system 400.

SWITCHING STRATEGY	EXEMPLARY SWITCHING LOSS
Transition Switching Strategy 204	> 50% switching of switch 108 in the troughs of primary supply voltage V_X
Constant Period Switching Strategy 302	50% switching of switch 108 in the troughs of primary supply voltage V_X
Efficient Control Signal Period Generator 408	< 50% switching of switch 108 in the troughs of primary supply voltage V_X.

Table 1

(47) As previously stated, in at least one embodiment, the troughs of primary supply voltage V_X are below primary supply RMS voltage V_{X_RMS} and, for a sine wave, are between phase angles 0°-45° and between phase angles 135°-180°.

(48) Figure 6 depicts an exemplary efficient period-instantaneous primary supply voltage V_X correlation strategy 600 for efficient control signal period generator 408. Referring to Figures 5 and 6, as primary supply voltage V_X increases towards a peak voltage $\sqrt{2} \cdot V_{X\_RMS}$, the power transfer from voltage source 404 to switching power converter 402 increases nonlinearly. For any given value of primary supply voltage V_X and power output by switching power converter 402, there is an optimum switching period TT. The optimum period generally increases in the troughs of primary supply voltage V_X. If the period TT is too short, there is excess switching loss. If the period TT is too long, there will be excessive loss in resistive parasitics, such as the respective resistances of switch 108 and inductor 110 and in core losses of inductor 110. The efficient period-instantaneous primary supply voltage V_X correlation strategy 600 provides a strategy for determining the period TT as a function of the instantaneous primary supply voltage V_X. The actual value of an optimal value of period TT is a matter of design choice and is, for example, dependent upon the values of the components of switching power converter 402 such as the characteristics of inductor 110, switch 108, capacitor 106, and diode 111 along with the instantaneous primary supply voltage V_X, the primary supply RMS voltage V_{X_RMS}, and the power transferred to load 112. Power control system 400 is, in at least one embodiment, more efficient than conventional power control system 100 because the switching frequency of switch 108 increases as more power is supplied by voltage source 404, thus, the controller achieves an efficient correlation between the switching period with associated switching losses of switch 108.

(49) In at least one embodiment, the switching power converter 402 operates in DCM. The frequency 1/TT of switch control signal CS_1 is, for example, between 10 kHz and 130 kHz. The period TT of switch control signal CS_1 and, thus, the duration of each cycle of inductor i_L depicted in inductor current i_L waveform 504 is exaggerated for visual clarity.

(50) Figure 7 depicts exemplary, correlated waveforms 700 between an exemplary inductor current i_L and switch control signal CS_1. During the time T1 of each pulse

width of switch control signal CS_1, inductor current i_L rises as energy is transferred from voltage source 404 to inductor 110. During the flyback time T2, inductor current i_L decreases as the inductor stored energy charges capacitor 106. The average inductor current i_{L_AVG} 706 tracks primary supply voltage V_X to provide power factor correction.

(51) Figure 8 depicts a PFC and output voltage controller 800, which represents one embodiment of PFC and output voltage controller 406. PFC and output voltage controller 800 determines switch control signal CS_1 in accordance with the switch control signal generation strategy implemented by control signal period generation strategy module 802. Efficient control signal period generation strategy module 802 represents one embodiment of efficient control signal period generator 408. In at least one embodiment, the control signal period generation strategy module 802 generates TT as a function of at least one of: the instantaneous primary supply voltage V_X and the estimated power delivered to load 112. In at least one embodiment, the control signal period generation strategy module 802 generates TT as a function of both the primary supply voltage V_X and the estimated power delivered to load 112.

(52) The PFC and output voltage controller 800 determines the period TT and pulse width T1 of switch control signal CS_1 to, for example, provide power transfer efficiency and power factor correction for switching power converter 402. In at least one embodiment, the estimated power delivered to load 112 is represented by "K", the output value of load power demand estimator 803 in the voltage control loop 418. In at least one embodiment, the square of the pulse width period T1, i.e. $T1^2$, is determined in accordance with Equation 1:

$$T1^2 = \frac{2 \cdot L}{V_{X\_RMS}{}^2} \cdot K \cdot TT \cdot \left(1 - \frac{V_X}{V_C}\right) \qquad 1$$

(53) "T1" is the pulse width (on-time) of the control signal CS_1. "L" represents an inductor value of inductor 110. V_{X_RMS} represents the primary supply RMS voltage V_{X_RMS}. "K" represents an estimate of the power demand of load 112 as determined by load power demand estimator 803. "TT" is the period of control signal CS_1 as generated by control signal period generation strategy module 802. "V_X" is a sampled value of the current value of primary supply voltage V_X. "V_C" is a sampled value of

the output voltage V_C. In the preferred embodiment, this calculation will be performed in fixed-point arithmetic with appropriately scaled values and work lengths.

(54) The RMS value generator 804 determines primary supply RMS voltage V_{X_RMS} from a sampled primary supply voltage V_X. Module 806 receives the primary supply RMS voltage V_{X_RMS} value and determines $2 \cdot L/(V_{X\_RMS}^2)$. "$2 \cdot L/(V_{X\_RMS}^2)$" represents a scaling factor. Boost factor module 808 determines a boost factor $(1-V_X/V_C)$. Multiplier 810 multiplies switch control signal CS_1, period TT, the output value of module 806, the output value of boost factor module 808, and estimated power demand K to generate $T1^2$. Nonlinear delta-sigma modulator 812 determines the pulse width T1 of switch control signal CS_1. Pulse width modulator (PWM) 814 receives the pulse width T1 and period TT and generates switch control signal CS_1 so that switch control signal CS_1 has a pulse width T1 and a period TT.

(55) In at least one embodiment, to ensure that switching power converter 402 operates in DCM, the value L of inductor 110 is set in accordance with Equation [2]:

$$L = V_{min}^2/[(P_{max} \cdot J) \cdot (2 \cdot f_{max}) \cdot \left[1 - \sqrt{2}\left(\frac{V_{min}}{V_{cap}}\right)\right] \qquad [2].$$

(56) "L" is the value of the inductor 110. "V_{min}" is the minimum expected primary supply RMS voltage V_{X_RMS}. "P_{max}" is the maximum power demand of load 112. "J" is an overdesign factor and any value greater than 1 indicates an overdesign. In at least one embodiment, "J" is 1.1. "f_{max}" is a maximum frequency of control signal CS_1. "V_C" is a nominal expected output voltage V_C. The flyback time T2 can be determined in accordance with Equation [3]:

$$T2 = \frac{V_X}{V_C - V_X} \qquad [3].$$

(57) In at least one embodiment, to avoid saturation of inductor 110, the value L of inductor 110 is chosen so that a peak inductor current, i_{L_PEAK} is greater than or equal to the greatest value of $V_X \cdot T1/L$. Generally, the peak inductor current i_{L_PEAK} occurs at full output power at the peak of primary supply voltage V_X during low line voltage operation.

(58) The efficient control signal period generation strategy used by PFC and output voltage controller 406 to determine a period of the switch control signal CS_1 is a

matter of design choice and can be set to optimize to the efficiency of switching power converter 402.

(59) Additionally, in at least one embodiment, the range of possible primary supply voltage levels also influences the time of period TT. For example, to remain in DCM operation, the period TT is increased for high line voltage conditions in order to remain in DCM operation.

(60) Figures 9-13 depict exemplary efficient period-instantaneous primary supply voltage V_X correlation strategies. The particular strategy used to provide an efficient period-instantaneous primary supply voltage V_X correlation depends on a number of operational factors such as the component values of a power control system, such as power control system 400, operational frequencies, and power delivered to load 112. Figures 9-13 illustrate a variety of strategies that provide efficient period-instantaneous primary supply voltage V_X correlation. Other period-instantaneous primary supply voltage V_X correlation strategies that inversely relate a trend of the switch control signal CS_1 period and the instantaneous primary supply voltage V_X can be used is a matter of design choice based, for example, on operational parameters of a power control system.

(61) Figure 9 depicts efficient period-instantaneous primary supply voltage V_X correlation strategy 900. The period TT decreases linearly from primary supply voltage V_X equal to 0 to primary supply voltage V_X equal to $0.75 \cdot \sqrt{2} \cdot V_{X\_RMS}$ and remains constant until primary supply voltage V_X equals $\sqrt{2} \cdot V_{X\_RMS}$. The constant period TT above voltage V_B sets an upper limit on the switching frequency of switch control signal CS_1 to, for example, prevent excessive switching losses of switch 108.

(62) Figure 10 depicts efficient period-instantaneous primary supply voltage V_X correlation strategy 1000. The efficient period-instantaneous primary supply voltage V_X correlation strategy 1000 maintains a constant switch control signal CS_1 period TT until primary supply RMS voltage V_{X_RMS} equals $0.25 \cdot \sqrt{2} \cdot V_{X\_RMS}$, decreases linearly thereafter until primary supply RMS voltage V_{X_RMS} equals $0.75 \cdot \sqrt{2} \cdot V_{X\_RMS}$, and then remains constant until primary supply RMS voltage V_{X_RMS} equals $\sqrt{2} \cdot V_{X\_RMS}$. The constant period TT above voltage V_A sets an upper limit for the switching frequency of switch control signal CS_1 to, for example, prevent excessive switching losses of switch 108. The constant period TT below voltage V_B sets a lower limit on

the switching frequency of switch 108 to, for example, avoid frequencies in a human audible frequency band.

(63) Figure 11 depicts efficient period-instantaneous primary supply voltage V_X correlation strategy 1100. The efficient period-instantaneous primary supply voltage V_X correlation strategy 1100 is a step function, and, thus, period TT need only be determined upon the transition from step to step.

(64) Figure 12 depicts efficient period-instantaneous primary supply voltage V_X correlation strategy 1200. The efficient period-instantaneous primary supply voltage V_X correlation strategy 1200 initially increases as primary supply RMS voltage V_{X_RMS} increases from 0 and then nonlinearly decreases as primary supply voltage V_X approaches $\sqrt{2}\cdot V_{X\_RMS}$. Even though efficient period-instantaneous primary supply voltage V_X correlation strategy 1200 briefly increases, efficient period-instantaneous primary supply voltage V_X correlation strategy 1200 causes the period TT of the switch control signal CS_1 to trend inversely to the instantaneous primary supply voltage V_X. In at least one embodiment, the efficient period-instantaneous primary supply voltage V_X correlation strategy 1200 causes the inductor 110 to get close to saturation.

(65) Figure 13 depicts efficient period-instantaneous primary supply voltage V_X correlation strategy 1300. The efficient period-instantaneous primary supply voltage V_X correlation strategy 1300 generally follows a decreases quadratically until primary supply voltage V_X equals $\sqrt{2}\cdot V_{X\_RMS}$.

(66) The particular period-power transfer correlation strategy used by efficient control signal period generator 408 is a matter of design choice and can be tailored to meet, for example, efficiency, power factor correction, computation complexity, and component characteristics. In the preferred embodiment, period generator 408 is implemented in digital logic and receives digitized representations of input values. The efficient control signal period generator 408 can generate the switch control signal CS_1 period TT in any of a number of ways. For example, the period-instantaneous primary supply voltage V_X strategy used by control signal period generation strategy module 802 can be stored as an algorithm, and control signal period generation strategy module 802 can determine the switch control signal CS_1 period TT in accordance with the algorithm. In another embodiment, the period-

power transfer correlation strategy can be stored in an optional memory 816. In at least one embodiment, the memory 816 includes a look-up table that correlates values of the period TT and values of primary supply voltage V_X. The control signal period generation strategy module 802 can then retrieve the value of period TT based on the value of primary supply voltage V_X.

(67) In at least one embodiment, the PFC and output voltage controller 800 is implemented as a programmable PFC and output voltage controller as described in U.S. Patent Application Serial No. 11/967,275, entitled “Programmable Power Control System”, filing date December 31, 2007, assignee Cirrus Logic, Inc., and inventor John L. Melanson. U.S. Patent Application Serial No. 11/967,275 includes exemplary systems and methods and is herby incorporated by reference in its entirety. As the optimum period depends upon the design choice of switching components, allowing programmability of the efficient period control algorithm allows each design to be optimized for efficiency while utilizing the same integrated circuit embodiment of PFC and output voltage controller 800.

(68) Figure 14 depicts nonlinear delta-sigma modulator 1400, which represents one embodiment of nonlinear delta-sigma modulator 812. The nonlinear delta-sigma modulator 1400 models a nonlinear power transfer process of switching power converter 402. The nonlinear power transfer process of switching power converter 402 can be modeled as a square function, x^2. Nonlinear delta-sigma modulator 1400 includes a nonlinear system feedback model 1402 represented by x^2. The output of feedback model 1402 is the square of delay-by-one quantizer output signal T1, i.e. $[T1(n-1)]^2$. Delay z^{-1} 1406 represents a delay-by-one of quantizer output signal T1. Negative $[T1(n-1)]^2$ is added to $T1^2$ by adder 1412. The nonlinear delta-sigma modulator 1400 includes a compensation module 1404 that is separate from quantizer 1408. The nonlinearity compensation module 1404 processes output signal u(n) of the loop filter 1410 with a square root function $x^{1/2}$ to compensate for nonlinearities introduced by the nonlinear feedback model 1402. The output c(n) of compensation module 1404 is quantized by quantizer 1408 to generate pulse width T1 for switch control signal CS_1.

(69) Figure 15 depicts a proportional integrator (PI) compensator 1500, which represents one embodiment of load power demand estimator 803. The PI

compensator 1500 generates the load power demand signal K. The load power demand signal K varies as the difference between a reference voltage V_{REF} and the output voltage V_C, as represented by error signal e_v from error generator 1501, varies. The reference signal V_{REF} is set to a desired value of output voltage V_C. The PI compensator 1500 includes an integral signal path 1502 and a proportional signal path 1504. The integral signal path 1502 includes an integrator 1506 to integrate the error signal e_v, and a gain module 1508 to multiply the integral of error signal e_v by a gain factor g2 and generate the integrated output signal I_{PW}. The proportional path 1504 includes a gain module 1510 to multiply the error signal e_v by a gain factor g1 and generate the proportional output signal P_{PW}. Adder 1512 adds the integrated output signal I_{PW} and the proportional output signal P_{PW} to generate the load power demand signal K.

(70) The values of gain factors g1 and g2 are a matter of design choice. The gain factors g1 and g2 affect the responsiveness of PFC and output voltage controller 406. Exemplary values of gain factors g1 and g2 are set forth in the emulation code of Figures 8-31 of U.S. Patent Application Serial No. 11/967,269, entitled "Power Control System Using a Nonlinear Delta-Sigma Modulator with Nonlinear Power Conversion Process Modeling", filed December 31, 2007, assignee Cirrus Logic, Inc., and inventor John L. Melanson. U.S. Patent Application Serial No. 11/967,269 describes exemplary systems and methods and is incorporated herein by reference in its entirety. Faster response times of the PFC and output voltage controller 406 allow the switch control signal CS_1 to more rapidly adjust to minimize the error signal e_v. If the response is too slow, then the output voltage V_C may fail to track changes in power demand of load 112 and, thus, fail to maintain an approximately constant value. If the response is too fast, then the output voltage V_C may react to minor, brief fluctuations in the power demand of load 112. Such fast reactions could cause oscillations in PFC and output voltage controller 406, damage or reduce the longevity of components, or both. The particular rate of response by proportional integrator 1500 is a design choice.

(71) Figures 16 and 17 depict respective exemplary embodiments of RMS value generator 804. The RMS value of primary supply voltage V_X is the square root of the average of the squares of primary supply voltage V_X. RMS value generator 1600

receives a set $\{V_X\}$ samples of primary supply voltage V_X during a cycle of primary supply voltage V_X and squaring module 1602 squares each sample of primary supply voltage to determine a set $\{V_X^2\}$. Low pass filter 1604 determines a mean $V_X{}^2{}_{\_MEAN}$ of the set $\{V_X^2\}$. Square root module 1606 determines the square root of $V_X{}^2{}_{\_MEAN}$ to determine the primary supply RMS voltage V_{X_RMS}.

(72) The RMS value generator 1700 receives the primary supply voltage V_X and peak detector 1702 determines a peak value V_{X_PEAK} of primary supply voltage V_X. Since primary supply voltage V_X is a sine wave in at least one embodiment, multiplying V_{X_PEAK} by $\sqrt{2}/2$ with multiplier 1704 generates primary supply RMS voltage V_{X_RMS}. In at least one embodiment, as the exact value of V_{X_PEAK} is not critical, the determination of V_{X_PEAK} by RMS value generator 1700 is generally adequate.

(73) Figure 18 depicts a PFC and output voltage controller 1800 that represents one embodiment of PFC and output voltage controller 406. In at least one embodiment, multi-way function control signal period generation strategy module 1802 determines the period TT of switch control signal CS_1 as a one-way, two-way, or three-way function of the Period Determination Variables. As primary supply RMS voltage V_{X_RMS} increases the average input current, and hence the average inductor current i_L required to supply a given amount of power decreases. For example, for primary supply RMS voltage $V_{X\_RMS} = 120V$, to supply 30 watts of power, the input equals 250 mA, i.e. $P=V\cdot I$. For primary supply RMS voltage $V_{X\_RMS} = 240V$, to supply 30 watts of power, the RMS inductor current i_{L_RMS} equals 125 mA. Thus, the period TT of switch control signal CS_1 can be increased with increasing values of primary supply RMS voltage V_{X_RMS}, which decreases the frequency of switch control signal CS_1. Decreasing the frequency of switch control signal CS_1 increases the efficiency of power control system 400. In at least one embodiment, PFC and output voltage controller 1800 functions the same way as PFC and output voltage controller 800 except the strategy module 1802 determines the period TT of switch control signal CS_1 as a one-way, two-way, or three-way function of the Period Determination Variables.

(74) Figures 19, 20, and 21 depict respective efficient period determination strategies 1900, 2000, and 2100 represents a three-way function of the Period

Determination Variables. The three-way function" indicates that all three of the Period Determination Variables are used to determine the period TT of switch control signal CS_1. Referring to Figure 19, the estimated power delivered to load 112 is greater than half (> 50%) of a maximum deliverable power to load 112. As the value of primary supply RMS voltage V_{X_RMS} increases, period determination strategy 1900 increases the value of period TT for a given primary supply RMS voltage V_{X_RMS} value. Additionally, the period TT also trends inversely relative to the instantaneous primary supply voltage V_X. The period determination strategy 1900 represents one embodiment of an efficient period determination strategy that can be utilized by the V_{X_RMS} based efficient control signal period generation strategy module 1802. The period-power transfer correlation strategies of Figures 10-13 can also be utilized by V_{X_RMS} based efficient control signal period generation strategy module 1802 by increasing the period TT of switch control signal CS_1 with increasing values of primary supply RMS voltage V_{X_RMS}.

(75) Figure 20 depicts an efficient period determination strategy 2000 that represents a three-way function of the Period Determination Variables. The estimated power delivered to load 112 ranges from greater than 20% to 50% of a maximum deliverable power to load 112. As the value of primary supply RMS voltage V_{X_RMS} increases, period determination strategy 2000 increases the value of period TT for a given primary supply RMS voltage V_{X_RMS} value. Additionally, the period TT also trends inversely relative to the instantaneous primary supply voltage V_X. The period determination strategy 2000 represents one embodiment of an efficient period determination strategy that can be utilized by the V_{X_RMS} based efficient control signal period generation strategy module 1802. The period-power transfer correlation strategies of Figures 10-13 can also be utilized by V_{X_RMS} based efficient control signal period generation strategy module 1802 by increasing the period TT of switch control signal CS_1 with increasing values of primary supply RMS voltage V_{X_RMS}.

(76) Figure 21 depicts an efficient period determination strategy 2100 that represents a three-way function of the instantaneous voltage levels of the Period Determination Variables. The estimated power delivered to load 112 ranges from 0% to 20% of a maximum deliverable power to load 112. As the value of primary supply RMS voltage V_{X_RMS} increases, period determination strategy 2000 increases the

value of period TT for a given primary supply RMS voltage V_{X_RMS} value. For primary supply RMS voltage V_{X_RMS} equal to 240V, if the relationship between period TT and the instantaneous primary supply voltage V_X at $\sqrt{2}\cdot 240$ at a constant rate as primary supply RMS voltage V_{X_RMS} decreased, the period TT would be 80 micro seconds at instantaneous primary supply voltage V_X equal 0 V. However, to keep the frequency of switch 108 above 20 kHz, the upper limit of the human audible frequency band, period determination strategy 2100 limits a maximum period TT to 50 micro seconds, i.e. 20 kHz. Additionally, the period TT also trends inversely relative to the instantaneous primary supply voltage V_X. The period determination strategy 2100 represents one embodiment of an efficient period determination strategy that can be utilized by the V_{X_RMS} based efficient control signal period generation strategy module 1802. The period-power transfer correlation strategies of Figures 10-13 can also be utilized by V_{X_RMS} based efficient control signal period generation strategy module 1802 by increasing the period TT of switch control signal CS_1 with increasing values of primary supply RMS voltage V_{X_RMS}.

(77) Figures 19-21 taken together depict an exemplary function of the period of the switch control signal switch control signal CS_1 trending inversely to estimated power delivered to load 112. Although a particular embodiment of the estimated power delivered to load 112 and the period TT of switch control signal CS_1 is depicted, the particular relationship where the period TT of switch control signal CS_1 varies inversely to the estimated power delivered to load 112 is a matter of design choice. Additionally, Figures 19-21 can be used to as a two-way function of (i) the primary supply voltage V_X and (ii) the primary supply RMS voltage V_{X_RMS}, while providing power factor correction (PFC) if the estimated power delivered to load 112 is held constant. Additionally, Figures 19-21 can be used as a one-way function of the primary supply RMS voltage V_{X_RMS}, while providing power factor correction (PFC) by using only inverse relationships between the primary supply RMS voltage V_{X_RMS} and the period TT of switch control signal CS_1.

(78) Thus, PFC and output voltage controller 406 achieves an efficient correlation between the switching period with associated switching losses and (i) the instantaneous power transferred to the switching power converter, (ii) the primary

supply voltage V_X, and/or (iii) the primary supply RMS voltage V_{X_RMS}, while providing power factor correction (PFC).

(79) Although the present invention has been described in detail, it should be understood that various changes, substitutions and alterations can be made hereto without departing from the spirit and scope of the invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A system comprising:

a controller to generate a switch control signal to control conductivity of a switch included in a switching power converter, wherein controlling conductivity of the switch causes an input current to the switching power converter to vary in approximate proportion to a time varying voltage source signal supplied to the switching power converter, wherein the controller comprises:

a period generator to determine a period of the switch control signal so that the period of the switch control signal varies in accordance with at least one of:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;

(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the time-varying voltage source signal; and

(iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal; and

a pulse width generator to determine a pulse width of the switch control signal in response to at least one of: (i) the determined period of the switch control signal, (ii) the instantaneous voltage levels of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter.

2. The system of claim 1 further comprising:

an input to receive the time-varying voltage source signal from a voltage source; and

the switching power converter, coupled to the controller, to convert the voltage source signal into an output voltage signal, the switching power converter comprising the switch to control power transfer from the voltage source to the switching power converter wherein the switching power further comprises an inductor coupled between the input and the switch and further comprises an output, wherein the switch causes a transfer of power from the voltage source to the inductor when the switch conducts and the switch causes a transfer of power to the load when the switch is nonconductive.

3. The system of claim 1 wherein the period generator is configured to determine a period of the switch control signal so that the period of the switch control signal varies in accordance with at least two of:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;

(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal; and

(iii) the period of the switch control signal trends directly with voltage levels of the time-varying voltage source signal.

4. The system of claim 1 wherein the period generator is configured to determine a period of the switch control signal so that the period of the switch control signal varies in accordance with:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;

(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal; and

(iii) the period of the switch control signal trends directly with the line voltage level of the time-varying voltage source signal.

5. The system of claim 1 wherein the trend of the period of the switch with respect to instantaneous voltage levels of the voltage source signal is linear.

6. The system of claim 1 wherein the trend of the period of the switch with respect to instantaneous voltage levels of the voltage source signal is non-linear.

7. The system of claim 1 wherein the trend of the period of the switch with respect to instantaneous voltage levels of the voltage source signal is based on a piece-wise linear step function.

8. The system of claim 1 wherein, for a 180 degree half-cycle of the time-varying voltage source signal, the switch control signal comprises multiple cycles and less than 50% of the cycles of the switch control signal occur when a magnitude of the time varying voltage source signal is less than a root mean square of the time varying voltage source signal.

9. The system of claim 1 wherein the controller further comprises:

an analog-to-digital voltage level detector to detect a value of the time-varying voltage source signal; and

the period generator comprises a function generator, coupled to the voltage level detector, to receive a digital detected voltage level value and generate a digital period control signal to control the period of the switch control signal.

10. The system of claim 9 wherein the function generator is configured to generate the period of the control signal as a function of estimated power delivered to a load coupled to the switching power converter, the instantaneous voltage levels of the voltage source signal, and the line voltage level of the time-varying voltage source signal.

11. The system of claim 1 wherein the line voltage level of the time-varying voltage source signal is represented as one of the members of a group consisting of: a root mean square value, an average value, and a peak value of the time-varying voltage source signal.

12. The system of claim 1 wherein a maximum period of the switch control signal differs from a minimum period of the switch control signal by a ratio of at least 2:1.

13. A method comprising:

generating a switch control signal to control conductivity of a switch included in a switching power converter, wherein controlling conductivity of the switch causes an input current to the switching power converter to vary in approximate proportion to a time varying voltage source signal supplied to the switching power converter;

determining a period of the switch control signal so that the period of the switch control signal varies in accordance with at least one of:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;

(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal; and

(iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal;

determining a pulse width of the switch control signal in response to at least one of: (i) the determined period of the switch control signal, (ii) the instantaneous voltage levels of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter; and

providing the switch control signal to the switching power converter.

14. The method of claim 13 further comprising:

receiving the time-varying voltage source signal from a voltage source;

receiving a sample of the instantaneous voltage level of the voltage source signal;

receiving a sample of the voltage level of the output voltage signal of the switching power converter;

converting the voltage source signal into an output voltage signal; and

supplying the output voltage signal to the load.

15. The method of claim 13 further comprising:

causing the switch to conduct during each period of the control signal in accordance with the pulse width of the switch control signal; and

causing the switch to be nonconductive during a remaining time of each period.

16. The method of claim 13 wherein determining a period of the switch control signal comprises determining a period of the switch control signal so that the period of the switch control signal varies in accordance with at least two of:

(i) the period of the switch control signal trends inversely to estimated power delivered to a load coupled to the switching power converter;

(ii) the period of the switch control signal trends inversely to instantaneous voltage levels of the voltage source signal; and

(iii) the period of the switch control signal trends directly with the line voltage level of the time-varying voltage source signal.

17. The method of claim 13 wherein determining a period of the switch control signal comprises determining a period of the switch control signal so that the period of the switch control signal:

(i) trends inversely to estimated power delivered to a load coupled to the switching power converter;

(ii) trends inversely to instantaneous voltage levels of the voltage source signal; and

(iii) trends directly with the line voltage level of the time-varying voltage source signal.

18. The method of claim 13 wherein determining a period of a switch control signal further comprises determining a period of a switch control signal so that the trend of the period of the switch with respect to instantaneous voltage levels of the voltage source signal is linear.

19. The method of claim 13 wherein determining a period of a switch control signal further comprises determining a period of a switch control signal so that the trend of the period of the switch with respect to instantaneous voltage levels of the voltage source signal is non-linear.

20. The method of claim 13 wherein determining a period of a switch control signal further comprises determining a period of a switch control signal so that the trend of the period of the switch with respect to instantaneous voltage levels of the voltage source signal is based on a piece-wise linear step function.

21. The method of claim 13 wherein the switching power converter includes an inductor coupled between an input and an output of the switching power converter, the method further comprising:

transferring power to the inductor when the switch conducts; and

transferring power to the output of the switching power converter when the switch is nonconductive.

22. The method of claim 13 further comprising:

determining multiple periods of the switch control signal during each 180 degree half-cycle of the time-varying voltage source signal so that less than 50% of the cycles of the switch control signal occur when a magnitude of the time varying voltage source signal is less than a root mean square of the time varying voltage source signal.

23. The method of claim 13 further comprising:

detecting a voltage level value of the time-varying voltage source signal; and

determining the period of the switch control signal comprises determining the period of the switch control signal in accordance with the detected voltage level.

24. The method of claim 13 wherein the line voltage level of the time-varying voltage source signal is represented as one of the members of a group consisting of: a root mean square value, an average value, and a peak value of the time-varying voltage source signal.

25. The method of claim 13 wherein determining a period of the switch control signal further comprises determining a period of the switch control signal so that a maximum period of the switch control signal differs from a minimum period of the switch control signal by a ratio of at least 2:1.

26. An apparatus comprising:

means for generating a switch control signal to control conductivity of a switch included in a switching power converter, wherein controlling conductivity of the switch causes an input current to the switching power converter to vary in approximate proportion to a time varying voltage source signal supplied to the switching power converter;

means for determining a period of the switch control signal so that the period of the switch control signal varies in accordance with at least one of:

(i) the period of the switch control signal trends inversely to instantaneous power transferred to the switching power converter;

(ii) the period of the switch control signal trends inversely to voltage level changes of the voltage source signal; and

(iii) the period of the switch control signal trends directly with a line voltage level of the time-varying voltage source signal; and

means for determining a pulse width of the switch control signal in response to at least one of: (i) the determined period of the switch control signal, (ii) a voltage level of the voltage source signal, and (iii) a voltage level of the output voltage signal of the switching power converter.

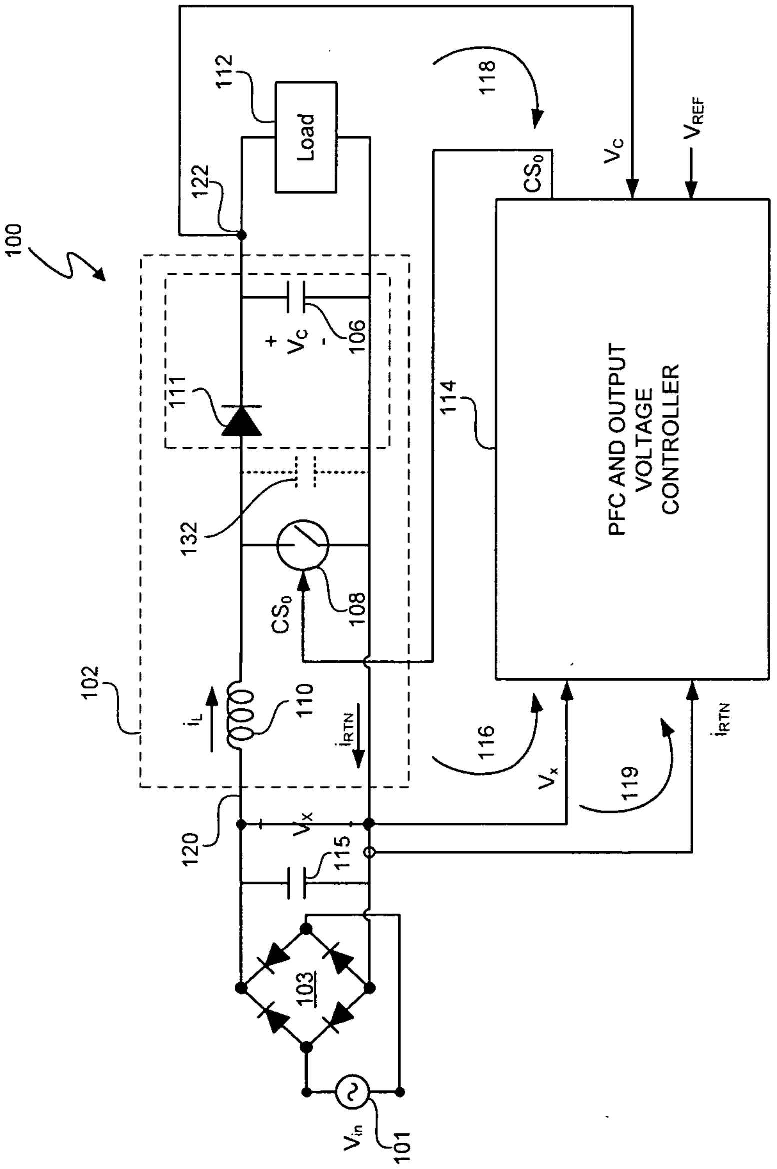

Figure 1 (prior art)

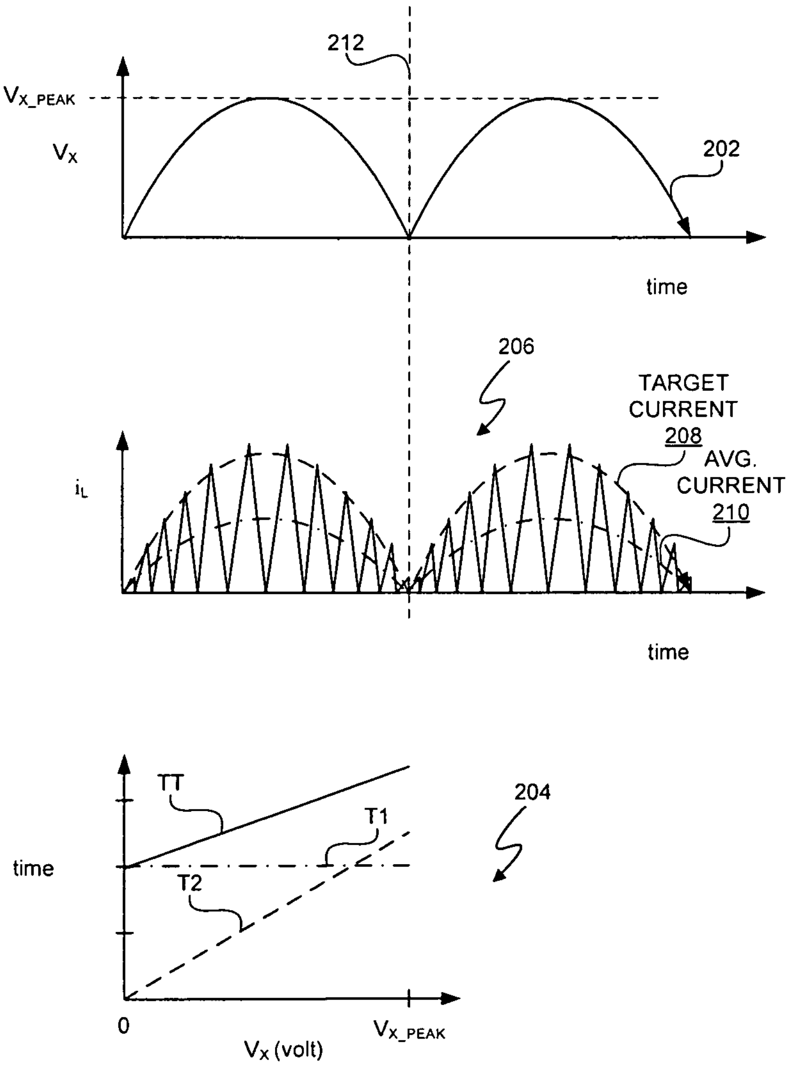

Figure 2 (prior art)

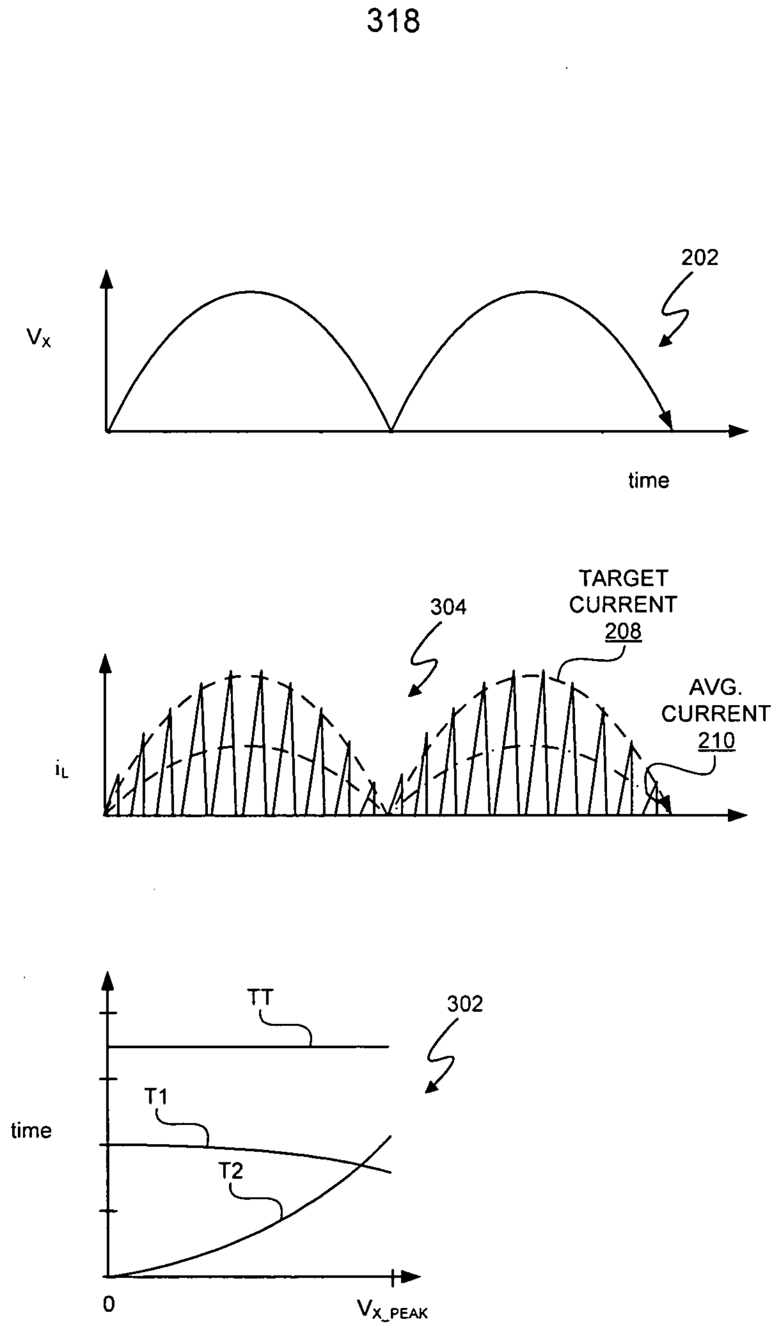
318
202
V_X
time
304
TARGET CURRENT 208
AVG. CURRENT 210
i_L
TT
302
T1
time
T2
0
V_{X_PEAK}
V_X (volt)

Figure 3

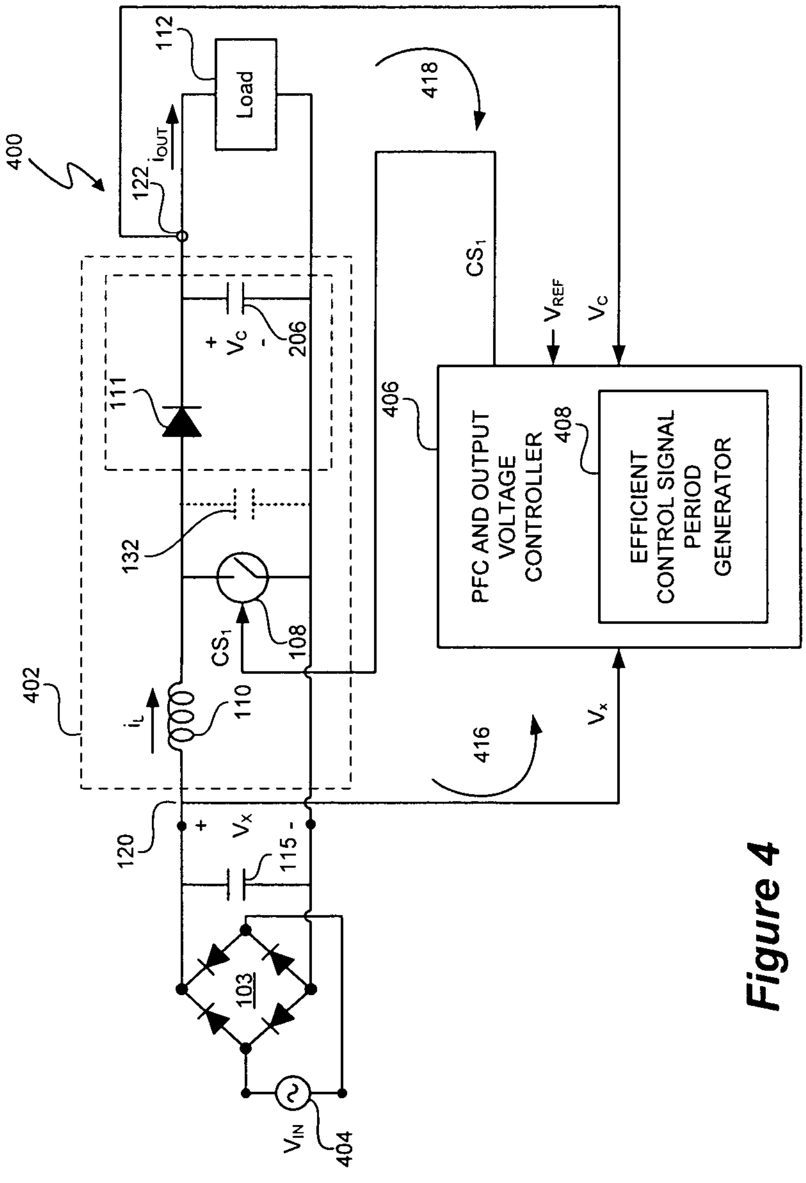
400
402
122
i_{OUT}
112
Load
418
111
+
V_C
-
206
CS₁
V_{REF}
V_C
406
PFC AND OUTPUT VOLTAGE CONTROLLER
408
EFFICIENT CONTROL SIGNAL PERIOD GENERATOR
132
CS₁
108
i_L
110
416
V_x
120
+
V_x
115
-
103
V_{IN}
404

Figure 4

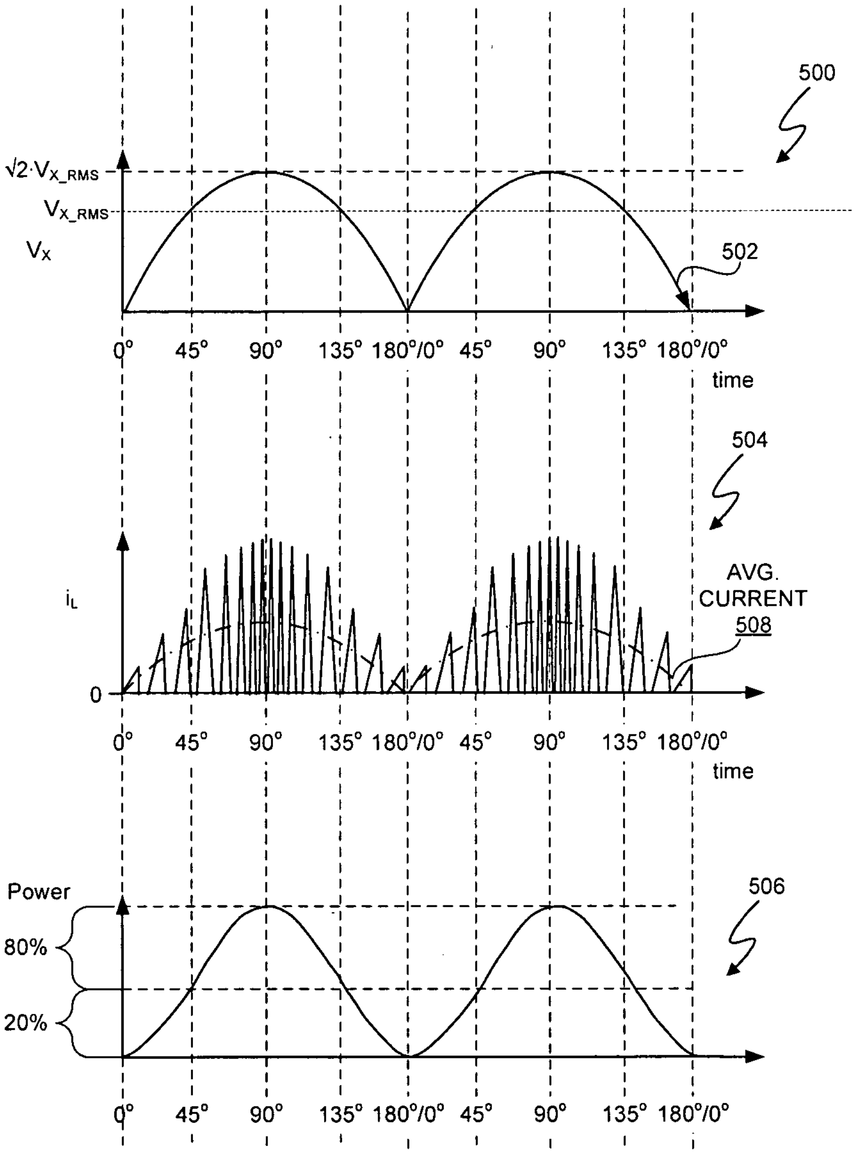
500
√2·V_X_RMS
V_X_RMS
V_X
502
0° 45° 90° 135° 180°/0° 45° 90° 135° 180°/0°
time
504
i_L
0
AVG. CURRENT 508
0° 45° 90° 135° 180°/0° 45° 90° 135° 180°/0°
time
506
Power
80%
20%
0° 45° 90° 135° 180°/0° 45° 90° 135° 180°/0°

Figure 5

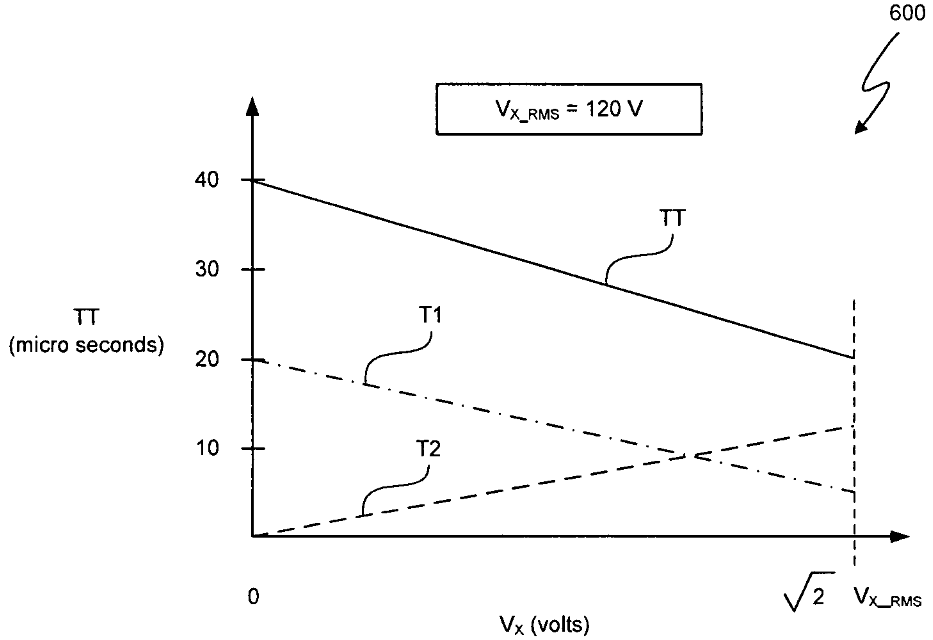
600
V_{X_RMS} = 120 V
TT
(micro seconds)
40
30
20
10
0
TT
T1
T2
$\sqrt{2}$ V_{X_RMS}
V_X (volts)

Figure 6

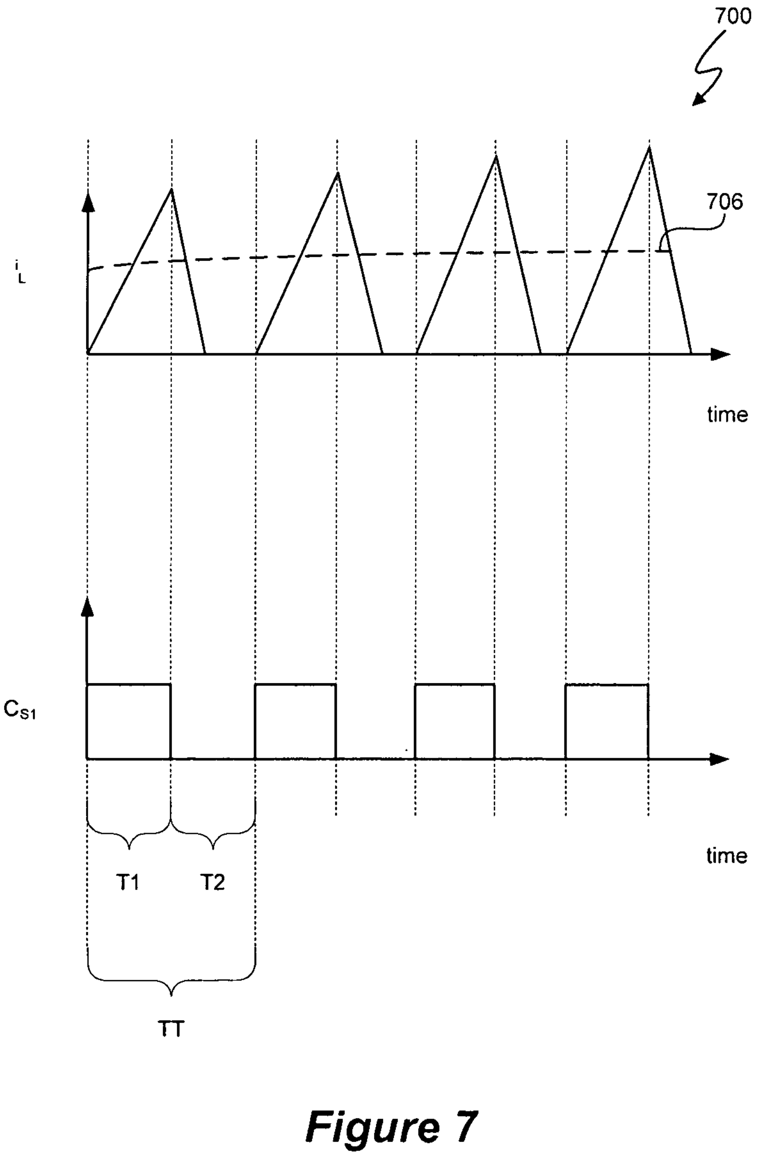

Figure 7

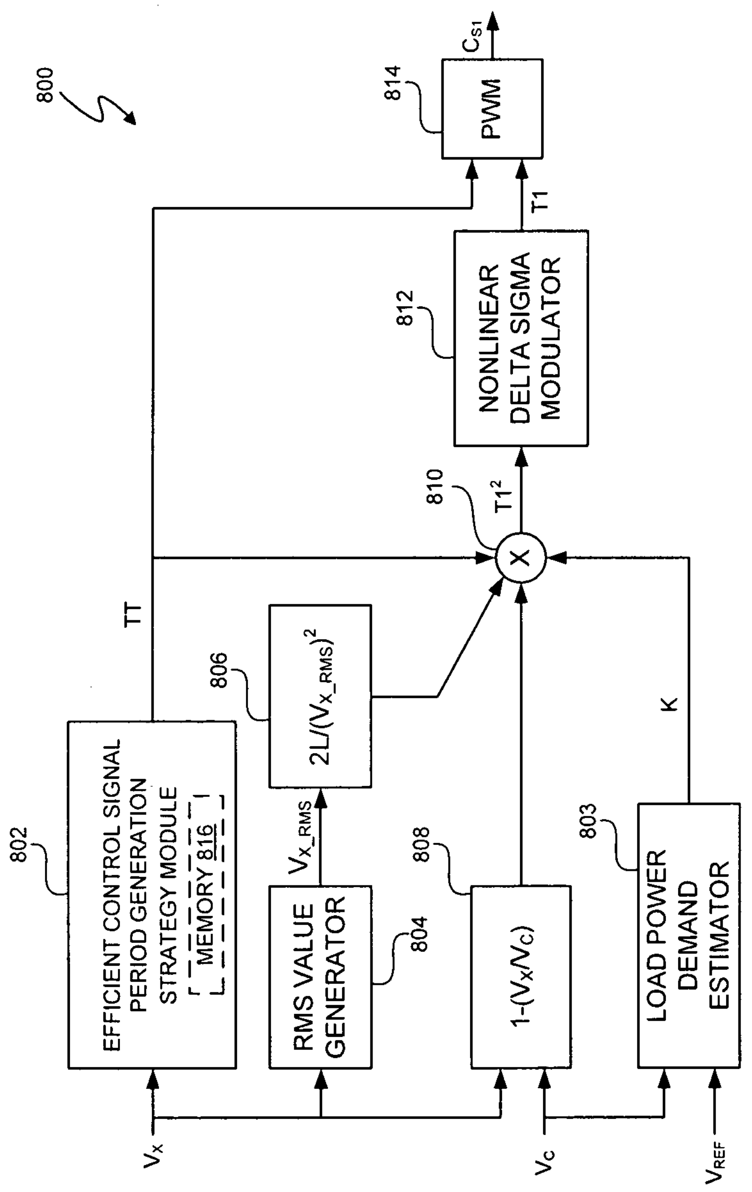
800
802
EFFICIENT CONTROL SIGNAL PERIOD GENERATION STRATEGY MODULE
MEMORY 816
804
RMS VALUE GENERATOR
V_{X_RMS}
806
$2L/(V_{X\_RMS})^2$
808
$1-(V_X/V_C)$
803
LOAD POWER DEMAND ESTIMATOR
K
TT
810
X
$T1^2$
812
NONLINEAR DELTA SIGMA MODULATOR
T1
814
PWM
C_{S1}
V_X
V_C
V_{REF}

Figure 8

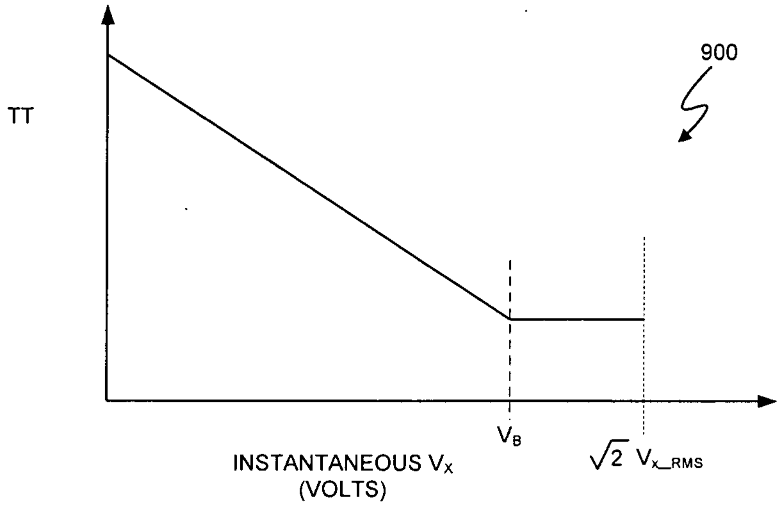

Figure 9

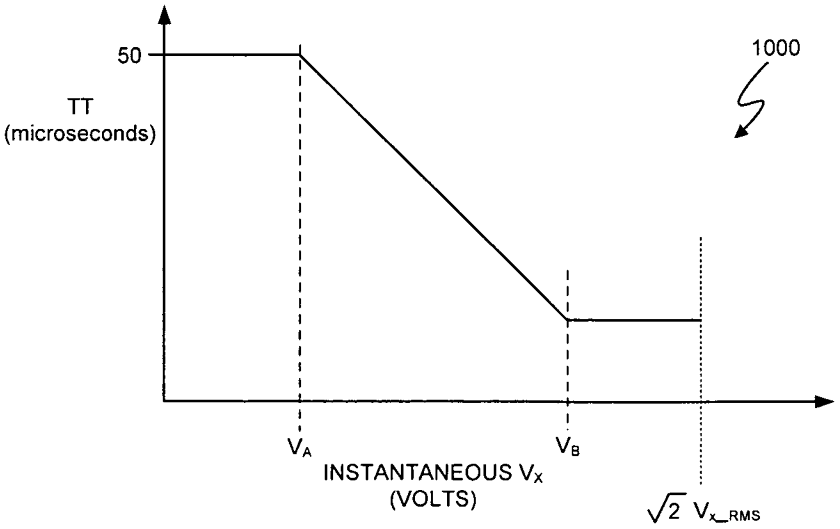

Figure 10

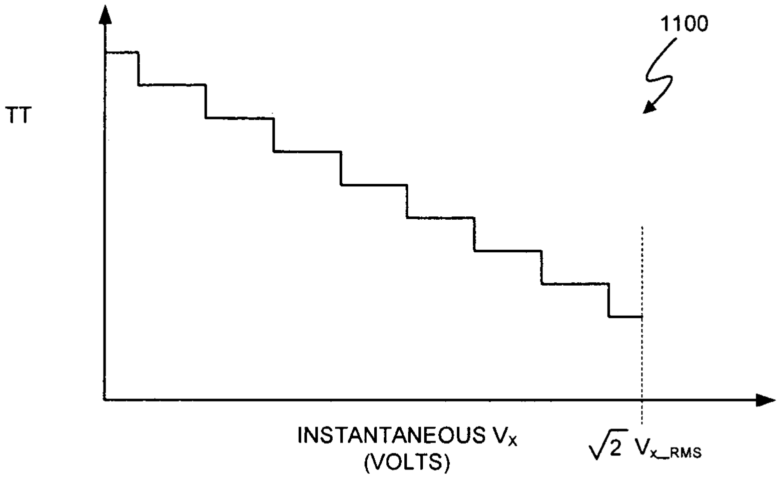

Figure 11

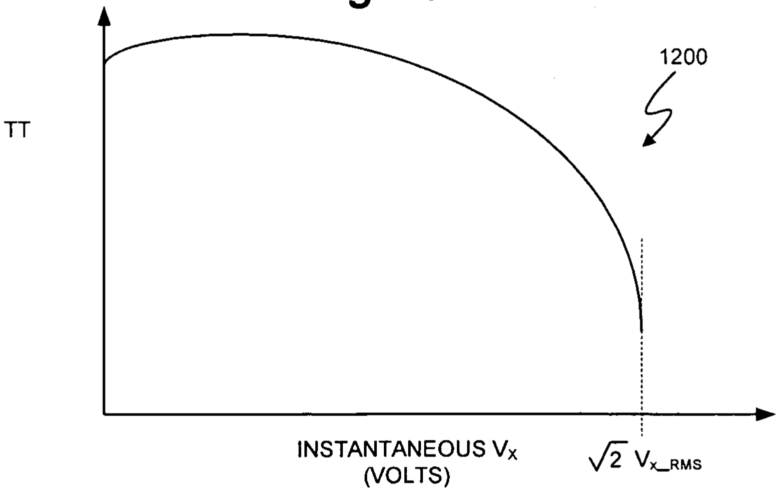

Figure 12

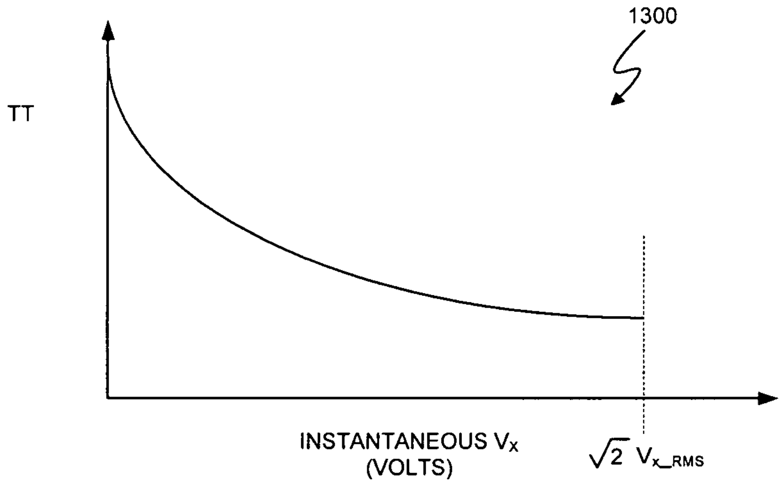

Figure 13

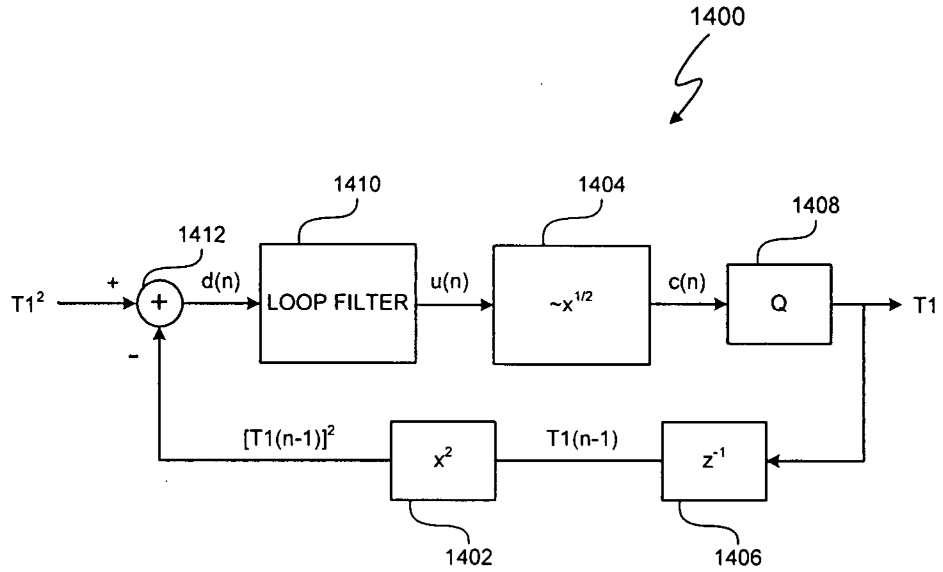
1400
1410
1404
1408
1412
T1²
+
-
d(n)
LOOP FILTER
u(n)
~x^1/2
c(n)
Q
T1
[T1(n-1)]²
x²
T1(n-1)
z^-1
1402
1406

Figure 14

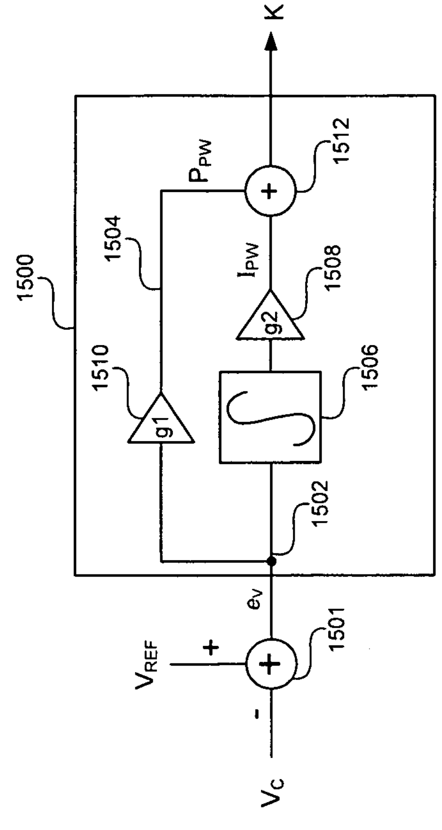
1500
1504
1510
1502
1506
1508
1512
1501
g1
g2
P_{PW}
I_{PW}
K
V_{REF}
+
-
V_C
e_V

Figure 15

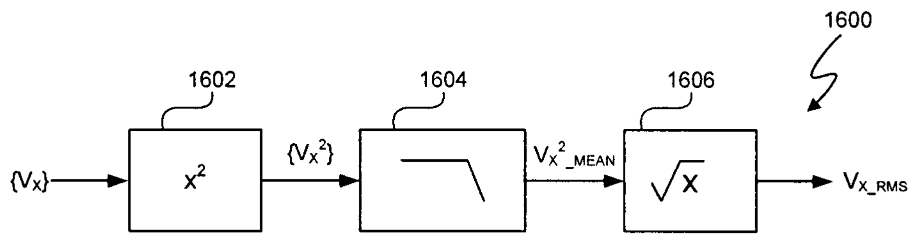

Figure 16

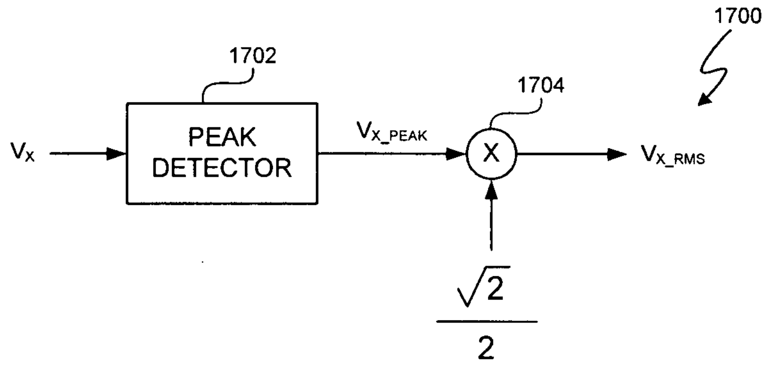

Figure 17

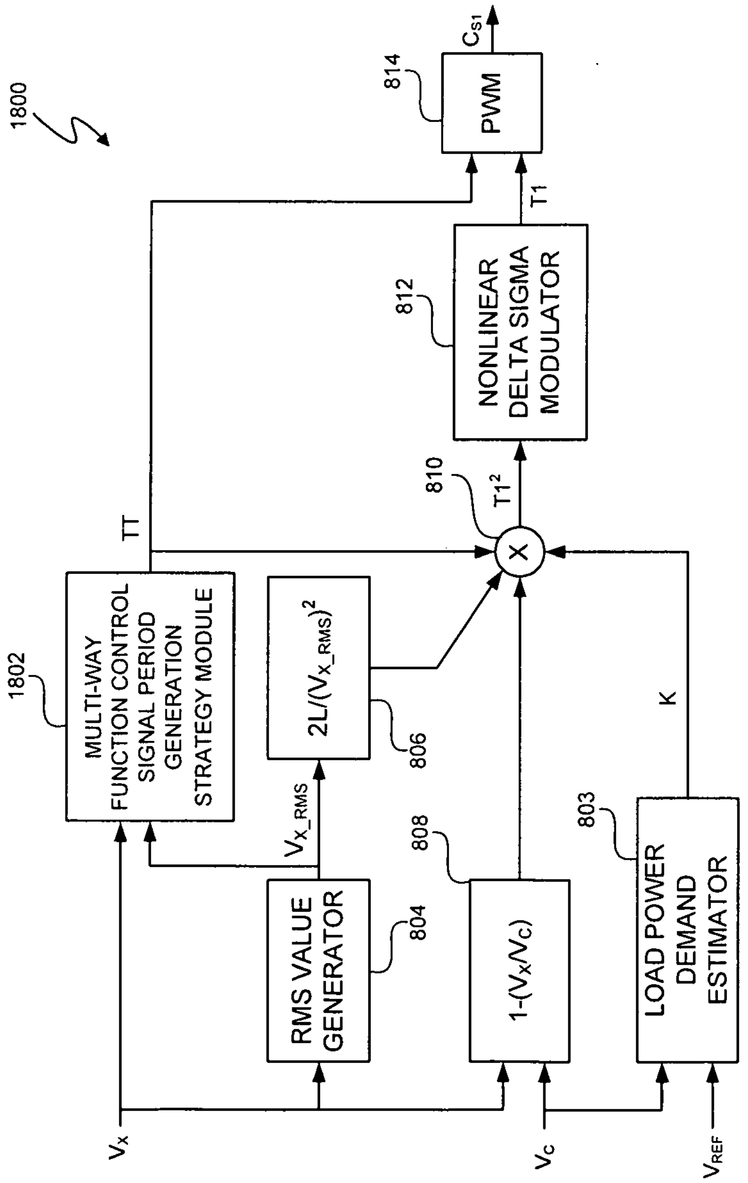
1800
1802
MULTI-WAY FUNCTION CONTROL SIGNAL PERIOD GENERATION STRATEGY MODULE
TT
814
PWM
C_{S1}
T1
812
NONLINEAR DELTA SIGMA MODULATOR
810
$T1^2$
X
806
$2L/(V_{X\_RMS})^2$
V_{X_RMS}
804
RMS VALUE GENERATOR
808
$1-(V_X/V_C)$
803
LOAD POWER DEMAND ESTIMATOR
K
V_X
V_C
V_{REF}

Figure 18

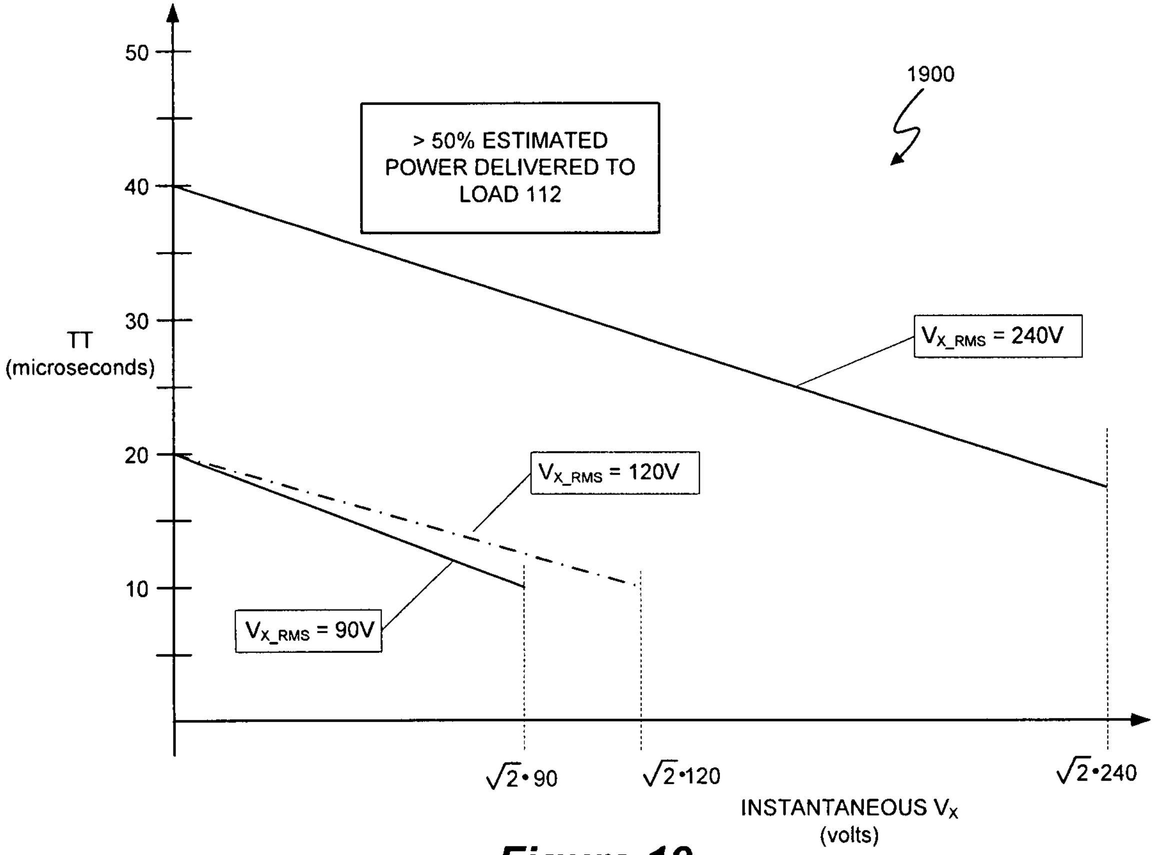
1900
> 50% ESTIMATED POWER DELIVERED TO LOAD 112
TT (microseconds)
50
40
30
20
10
V_{X_RMS} = 240V
V_{X_RMS} = 120V
V_{X_RMS} = 90V
$\sqrt{2}\cdot 90$
$\sqrt{2}\cdot 120$
$\sqrt{2}\cdot 240$
INSTANTANEOUS V_X (volts)

Figure 19

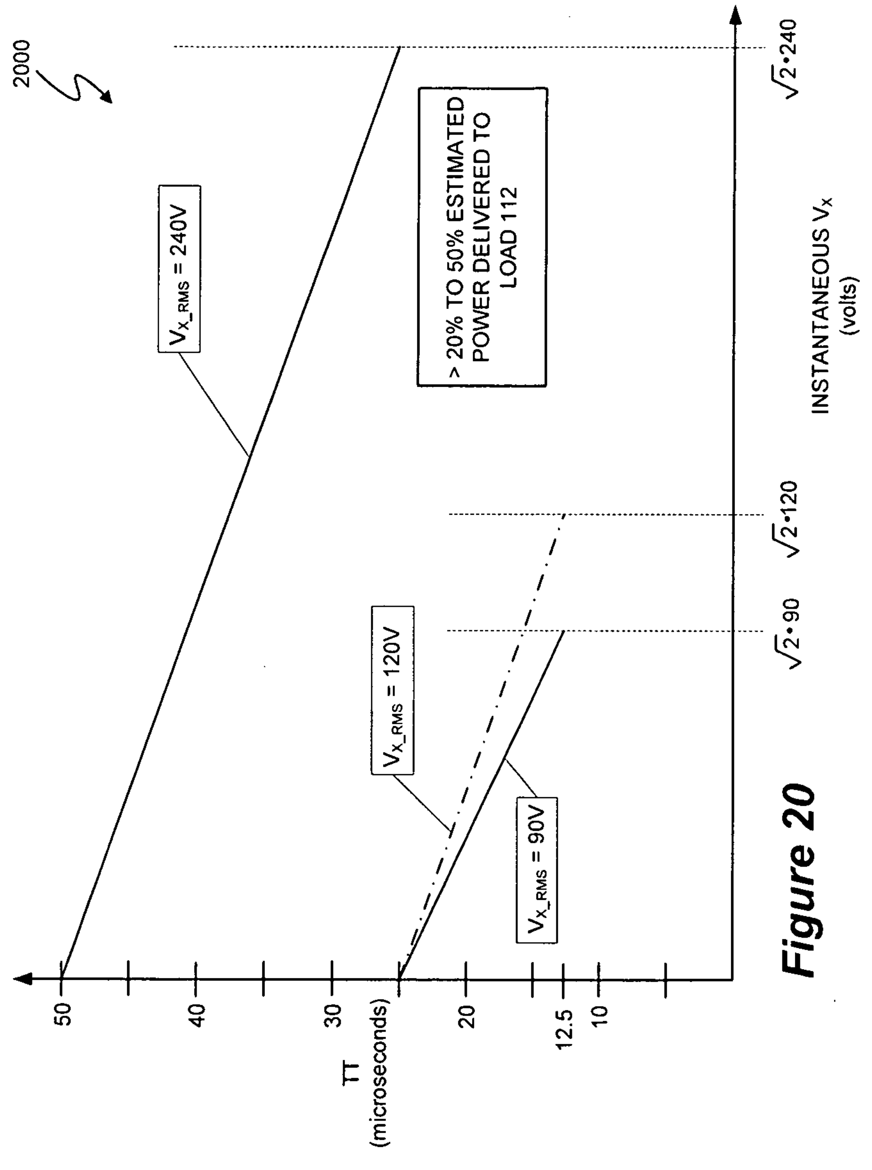
2000
V_{X_RMS} = 240V
> 20% TO 50% ESTIMATED POWER DELIVERED TO LOAD 112
V_{X_RMS} = 120V
V_{X_RMS} = 90V
TT (microseconds)
50
40
30
20
12.5
10
$\sqrt{2}\cdot 90$
$\sqrt{2}\cdot 120$
$\sqrt{2}\cdot 240$
INSTANTANEOUS V_X (volts)

Figure 20

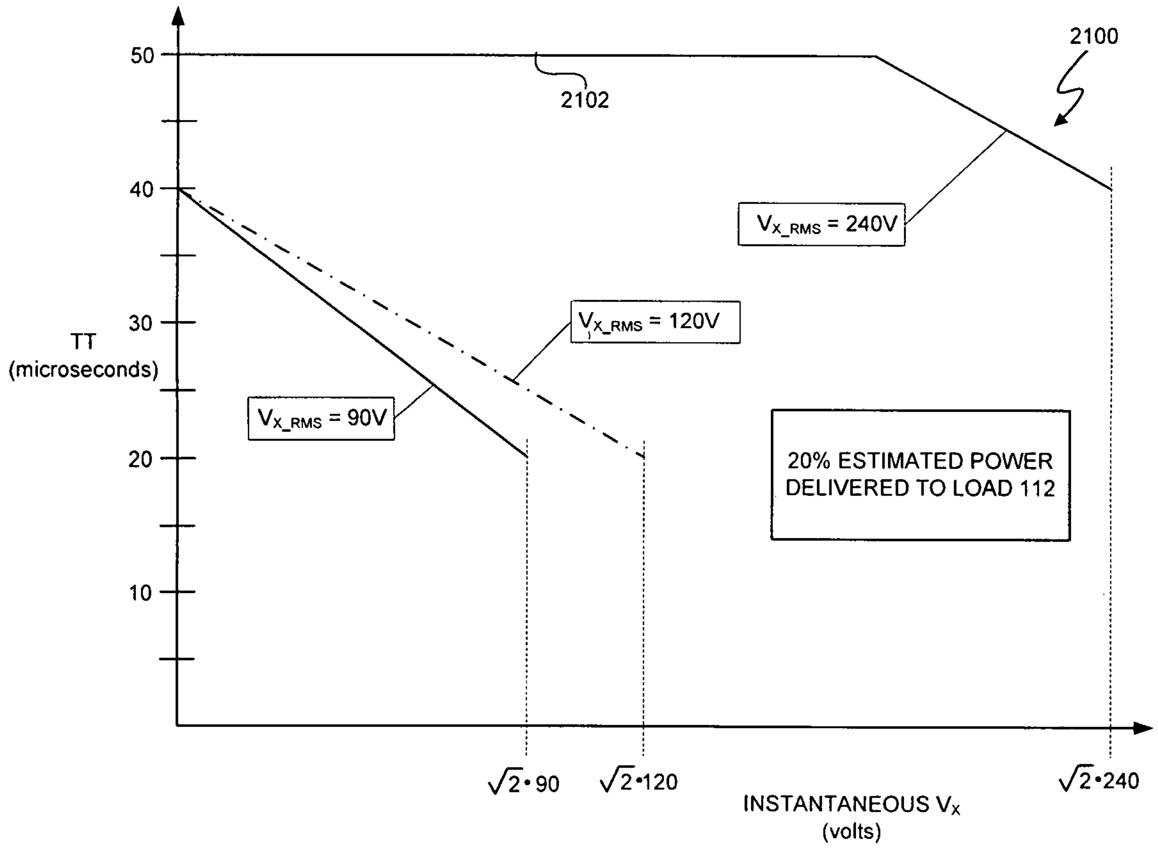
2100
2102
50
40
30
20
10
TT
(microseconds)
V_{X_RMS} = 240V
V_{X_RMS} = 120V
V_{X_RMS} = 90V
20% ESTIMATED POWER
DELIVERED TO LOAD 112
$\sqrt{2}\cdot 90$
$\sqrt{2}\cdot 120$
$\sqrt{2}\cdot 240$
INSTANTANEOUS V_X
(volts)

Figure 21

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/062428

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/42

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)
H02M H03K G05F

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y L	WO 2006/022107 A (SANKEN ELECTRIC CO LTD [JP]; TSURUYA MAMORU) 2 March 2006 (2006-03-02) & US 2007/103949 A1 (TSURUYA MAMORU [JP]) 10 May 2007 (2007-05-10) abstract paragraphs [0013] - [0016], [0046] - [0053], [0072]; figures 5,6,10	1-6,8, 12-19, 21-24,26 9
X	US 2005/057237 A1 (CLAVEL ROBERT [CA]) 17 March 2005 (2005-03-17) abstract; figure 2 paragraphs [0008], [0009], [0065] - [0089]	1,3,4, 11-13, 16,17, 24-26

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family 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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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search 26 August 2008	Date of mailing of the international search report 15/09/2008
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Braccini, Roberto

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/062428

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 768 655 B1 (YANG TA-YUNG [US] ET AL) 27 July 2004 (2004-07-27) abstract column 1, line 52 - column 2, line 43; figure 1 column 6, line 46 - line 49 -----	1,3,4, 13,16, 17,26
Y	PRODIC A ET AL: "Dead-zone digital controller for improved dynamic response of power factor preregulators" APEC 2003. 18TH. ANNUAL IEEE APPLIED POWER ELECTRONICS CONFERENCE AND EXPOSITION. MIAMI BEACH, FL, FEB. 9 - 13, 2003; [ANNUAL APPLIED POWER ELECTRONICS CONFERENCE], NEW YORK, NY : IEEE, US, vol. 1, 9 February 2003 (2003-02-09), pages 382-388, XP010631538 ISBN: 978-0-7803-7768-4 abstract; figure 1 -----	9

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2008/062428

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2006022107 A	02-03-2006	CN 1906839 A JP 2006067730 A US 2007103949 A1	31-01-2007 09-03-2006 10-05-2007
US 2007103949 A1	10-05-2007	CN 1906839 A JP 2006067730 A WO 2006022107 A1	31-01-2007 09-03-2006 02-03-2006
US 2005057237 A1	17-03-2005	NONE	
US 6768655 B1	27-07-2004	NONE	