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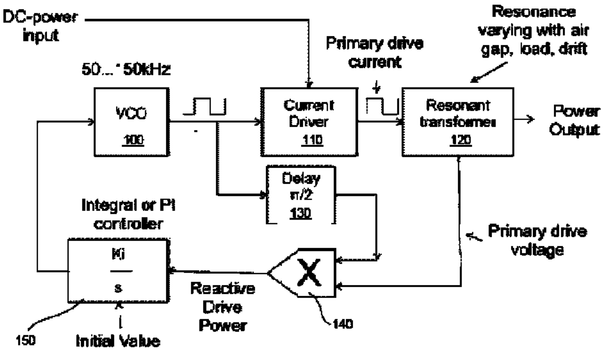
(54) Title **Method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler**

(57) Abstract

Method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler, where the driving frequency of the inductive coupler is controlled in such a way that reactive power from drive control in to the inductive coupler becomes close to zero, and utilizing the control of the close to zero reactive power to continuously minimizing switch-on voltage in switching power transistors as they connect and disconnect, and thus reducing switching loss.



Method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler

The present invention is related to a method for control of a parallel resonant current-driven inductive coupler, according to the preamble of claim 1.

The present invention is further related to a parallel resonant current-driven inductive coupler, according to the preamble of claim 10.

The present invention is especially related to a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler based on precise control of driving frequency to provide minimum reactive load in transformer. This drive strategy results in close to zero voltage switching and is minimizing switching loss as well as total loss.

Background

Precise control of driving frequency in a resonant inductive coupler is important, among others, for having as low loss as possible.

Inductive couplers normally use much higher magnetizing current than typical resonant power supplies. This due to the air gap between primary and secondary coil is larger than for regular power supplies. Larger air gap lowers the value of open-circuit impedance in the coupler, as this lies in parallel over the input voltage, reducing the impedance in this and increasing the magnetizing current.

The use of resonance with partly high Q-values is therefore usually favorable as this result in lower current through, and lower loss in the semi-conductor switches, but this complicates optimal switching both on the primary and secondary side. One still usually should go for a resonant design also at lower Q-values, as this generally results in lower loss in a power supply.

LLC resonant converters have a very unstable output voltage and are useless without feedback. A converter which also can operate without feedback is wanted for inductive couplers, as this will make such units simpler and less expensive.

The resonance frequency varies with temperature, load on the secondary side, - especially size of a variable air gap between primary and secondary side, which will be typical for inductive couplers. One will still have partly the same challenges in all resonant power supplies. The primary and secondary resonance circuit, for certain values of the coupling coefficient between them, will have two close by resonances, even if the circuits are identical, a well known behavior of this 4. order LC-circuit. The resonance frequency is dependent on the distance between the two core halves, and will also vary dependent on temperature, long-time drift and load, in addition to individual variations from unit to unit given by tolerances on used components.

It is known that it is favorable that the triggering of the driving switches/transistors is performed when it is lowest possible voltage at connection (known as ZVS, Zero Voltage Switching) and the lowest possible current at disconnection (known as ZCS, Zero Current Switching).

Dr. Aiguo Patrick Hu (Electrical Engineering univ. Auckland) was one of the first to address the problems with control of a current-driven resonant transfer in inductive couplers. Page 48-94 in the book "Wireless/Contactless Power supply" (ISBN 978-3-639-11673-1) is related to this. In some applications with not too high Q-value he mentions that one can go for the use of constant frequency, but it is enhanced that the losses can be partly high, and that control often is necessary. It is emphasized that control of the driving frequency is to prefer before control of the resonance frequency. Hu has developed an algorithm which calculates the optimal triggering point from the system parameters. The problem is that all the parameters in the model are not known, and especially this relates to the size of the air gap between primary and secondary as it often varies dynamically in use. By feedback from the secondary side, Hu mentions that one can use a phase-locked loop (PLL) which adjusts the driving frequency to a determined phase difference between the driving voltage/current and voltage out on the secondary side. It is further enhanced that this method can result in chaos-oscillations (at supercritical or split resonances connection between primary and secondary, resulting in dual resonance frequency). In addition one must have a fast communication back from the secondary side without time delay for transferring the time function of the voltage from the secondary side, making the method more useable for a regular resonant power supply than for a resonant inductive coupler.

Another person who has contributed to understanding resonant power supply is Professor Marian K. Kazimierczuk, e.g. with the book Resonant Power Converters (Write State University) - 1995 (ISBN 0-471-04706-6 pp-311-330). At page 312 he mentions that when the driving is equal to the resonance frequency the switches will be shut off and on at zero voltage, but he does not mention a device for adjusting this condition.

In the recent years many companies have proposed solutions for inductive couplers (wireless power).

WO 2015/062950 - Prediction of zero crossing (Philips/Peter Lürkens) - describes a converter which uses a square-shaped driving voltage. Voltage driving in this way is especially suitable when one desire to achieve high voltages but does not need any special control of the output voltage. At high Q-value in inductor/transformer one will almost get a constant current generator so that the output voltage from the converter increases approximately up to Q*Vinn at zero load on the secondary. This is probably acceptable for the use for driving an X-ray tube.

The control model used is observing the time derivative of the current before and after the square-shaped driving voltage is changed. This difference is close to zero when one disconnects at the right time (at zero current). One control by adjusting the integral of the difference between the time derivative of the current before and after reconnection to zero, in this way one will adjust towards zero current at disruption (ZCS). The two time derivatives of the current are determined by means of a number of comparators at certain relative current levels in relation to max current levels, and in addition phase displacement of the driving current signal, i.e. not by usual limited analogous or numerical differentiation operating directly on the time function of the current. The presumption for the triggering to be correct is that a pure inductive load is dominating the load, but the model for the inductor also includes some capacitance. The differentiation of the current must be good to get it to work well.

In US 2012/0249197 - Large Signal VCO (Markus Rehm) - it is described control of the frequency of an inductive coupler substantially intended for drifting one or more secondary circuits which are arranged over a larger geometrical area. Based on the constellation of different primary coils it is calculated an optimal driving frequency a priori. It is further made a self-oscillating circuit with feedback from the resonant part for control switches for supply of energy.

A phase-locked loop working back on capacity or inductivity will naturally regulate self-oscillating frequency close to resonance where the losses in the switching are lower. Rehm is still not focusing on that the losses should be very low, i.e. that one should lie as close to ZVS or ZCS as possible on the driving side, probably because this solution is not thought applied for high power levels where the consequences of high power loss is critical.

One will have improved control of the triggering point by observing voltage and current on the driving side, as e.g. is done by Lürkens.

By means of a phase-locked loop the capacity or inductivity in the resonant oscillatory circuit on the primary side is adjusted until the frequency is equal to the calculated optimal frequency given by how many secondary circuits are connected, and where they are physically placed. The solution of Rehm is thought used where magnetic energy is spread over a larger space providing energy transfer over a relatively large distance. In the solution of Rehm the control of capacity or inductance will require many switches with high current-carrying capacity, and a lot of driving electronics which will reduce the efficiency. The efficiency is especially important with regard to high power where this has both an economical/environmental demand aspect and results in reduced reliability of components due to high chip temperature, and increased size due to demand of transporting heat away.

Accordingly, there is a need for a method for control of a parallel resonant current-driven inductive coupler and a parallel resonant current-driven inductive coupler adapted for the use of parallel resonance and ZVS which are required in application as inductive connector, i.e. applications which require a more stable output voltage without using feedback control from the secondary to the primary side.

It is further a need for a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which is more robust for overvoltage at intermittent loss of (wireless) feedback than using standard LLC design.

There is further a need for a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which have a simple hardware function for both analog and digital implementation.

There is also a need for method for control of a parallel resonant current-driven inductive coupler and a parallel resonant current-driven inductive coupler providing an improved noiseless observation of the triggering point, compared to an advanced solution based on the state equations.

There is also a need for a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler having lower switching loss, as well as total loss, compared to the prior art solutions.

There is further a need for a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which is less affected by high harmonics than prior art solutions based on use of fixed comparator levels.

Object

The main object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which partly or entirely solve the above mentioned drawbacks of prior art.

An object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler adapted for the use of parallel resonance and ZVS required for applications as inductive electric connectors, where the field path is short and emission small, meeting regulations for EMI (electromagnetic interference) without solely using frequencies reserved for wireless power transfer.

Another object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler providing a reasonable stable output voltage without using feedback control from the secondary to the primary side.

Further, an object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and resonant inductive coupler being robust for overvoltage at intermittent loss of (wireless) feedback from the secondary side, thus easing design of the inductive coupler concerning overvoltage protection.

An object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which provide a simple hardware function for both analog and digital implementation.

There is further an object of the present invention to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler providing a noiseless observation of the triggering point by utilizing the entire time function of the voltage in calculation of the switching frequency/triggering point.

An object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler minimalizing the affect from high harmonics.

Another object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler providing accurate triggering of switching power transistors and low switching loss, as well as total loss.

Another important object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler providing a triggering control solution requiring little tuning to current parameters of a dynamic mathematical model of a system, thus providing a generic solution for a class of inductive couplers. Of particular value is the insensitivity to a changing air gap size between primary and secondary.

A further object of the present invention is to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which can be used for wireless transfer of power in harsh environments.

It is further an object of the present invention to provide a method for control of a parallel resonant current-driven inductive coupler and parallel resonant current-driven inductive coupler which will function optimally also when the input voltage contains significant ripple.

Further objects of the present invention will appear from the following description, claims and attached drawings.

The invention

A method for control of a parallel resonant current-driven inductive coupler according to the present invention is described in claim 1 and a parallel resonant current-driven inductive coupler according to the present invention is described in claim 10. Preferable features of the method and parallel resonant current-driven inductive coupler are described in the respective dependent claims.

The present invention is related to improvement of transfer of magnetic energy over an air gap of a resonant inductive coupler, particularly where the magnetic core types can be of type E, U or pot cores thus making it possible to avoid much magnetic field leakage to the surroundings. This makes it possible to conform to most EMI regulations even if the coupler operates in a larger frequency band.

The present invention includes, at primary side of the inductive coupler, a power source for supply of DC current/voltage to a drive control. The drive control according to a first embodiment of the present invention includes an electronic oscillator, current switching driver, 90 Deg phase displace unit, multiplying unit, integral or proportional integral (PI) controller, as well as primary side of a resonant transformer, arranged to form a driving circuit for the inductive coupler. The electronic oscillator can e.g. be a VCO (Voltage-controlled Oscillator) or on a SOC (System On Chip) with a high resolution built-in programmable PWM (Pulse-width modulation) which provides a driving voltage, e.g. square-shaped driving voltage with perfect symmetry. The PI-controller can also be implemented in a SOC whilst the multiplying unit will need some simple extra hardware for accurate timing to the PWM switching output from the SOC.

According to the present invention it is provided a method for control of the parallel resonant current-driven inductive coupler by utilizing a determined method for control of the opening and closing of switching power transistors of the current switching driver of the drive control on the primary side.

The present invention provides a solution where connection is performed at lowest possible voltage, but not necessarily such that the current is zero at disconnection. According to the present invention the switching power loss in the reconnection period will be low due to that instantaneous power is given by a product of current and voltage over the switching power transistors of the current switching driver.

A near optimal time point for reconnection will be when the current switching driver is in phase with the 1st harmonic of the voltage on the primary side of the resonant transformer, which is supported by simulations made by the applicant, as e.g. shown in Figure 6.

Accordingly, the method for control of a parallel resonant current-driven inductive coupler according to the present invention is based on control of driving frequency of the electronic oscillator such that reactive power from the driving circuit in to the resonant transformer becomes close to zero and utilizing the control of the close to zero reactive power to continuously minimizing switch-on voltage in the current drive control as the switching power transistors thereof connect and disconnect, thus reducing switching loss. The method according to the present invention further includes supplying an approximately square form driving current from the power source to the current switching driver and by means of the current switching driver phase displacing the driving current with 90 degrees in to the resonant transformer.

The method according to the present invention further includes phase displacing the driving current from the electronic oscillator by means of a phase displace unit and multiplying the phase displaced driving current with primary drive voltage of the resonant transformer to provide a measurement of reactive power with sign supplied to the primary side of the inductive coupler.

More specifically, the method includes measurement of the reactive power by multiplying the quadrature component of the driving current with primary voltage.

The method according to the present invention further includes averaging/integrating the measured reactive power by means of analog or digital processing.

According to a further embodiment of the method according to the present invention the method further includes adding proportional effect in addition to pure integral effect in the drive control for achieving a faster control to correct level when needed given by fast load or supply voltage changes. This comes at the expense of slightly higher switching loss given by enhanced noise in the observation of the triggering point. A low pass filter having a cutoff frequency far above the close to zero cross frequency of the drive controller loop may be added after the computation of reactive power if needed. This addition will be mandatory when using PI control instead of just I-control.

The method according to the present invention further includes using the product from the averaging/integrating and possibly proportional effect in a PI controller for adjusting the driving frequency to close to zero reactive power.

According to a further embodiment of the present invention the method may further include adding a fixed low offset to the measured reactive power for fine tuning of switching frequency/triggering point of the switching power transistors to minimize switching loss in the switching power transistors of the current switching driver. By this one achieve a weak inductive load situation for switching power transistors of the current switching driver. In this way one can ensure that one do not enter an area where the load is capacitive and the switching efficiency becomes lower.

According to a further embodiment of the present invention the switching power transistors preferably are fast GaN or SiC transistors so that full advantage is taken of the accurate switching control given by low switching times of these types of semiconductors.

According to a further embodiment of the present invention the method may further include finding offset to the measured reactive power by continuously searching for a temperature minimum on the switching power transistors of the current switching driver by pertubating small deviations on said offset by using a numerical search method. Such perturbations are supposed to be so small that the influence on the average total power loss will be neglectible, and occurring at a time interval longer than the typical thermal time constant of the switching power transistors.

According to a further embodiment of the method according to the present invention the method includes determining initial value of drive frequency for the controller based on last used quality controlled value, measured and stored in a supervision unit in the inductive coupler. This supervision unit is usually implemented in a SoC and measures current drive frequency, input voltage, input current, temperature on the switching power transistors, etc. From this information a quality controlled best initial value for the drive frequency is calculated and stored during power off of the unit. This value is used at the next startup of the inductive coupler.

According to a further embodiment of the method according to the present invention the method includes determining initial value of frequency for the controller based on a measurement of resonance frequency performed at low current-voltage-amplitudes as part of the turn-on procedure for the inductive coupler, i.e. before switching to full power on. This is of particular interest for determining important changes in air gap size since last power on of the unit.

According to a further embodiment of the method according to the present invention the method includes determining initial value of frequency for the controller based initial frequency at nominal distance between primary and secondary core.

According to a further embodiment of the method according to the present invention the method includes determining initial value of the frequency of the controller based on a measurement of input voltage from the power source and using this for correction of the measured resonance frequency at low drive amplitude. This correction function is a fixed empirical function, preferably determined during product development.

The determination of initial frequency can be used for ensuring that overcurrent is avoided during start-up. This can also be implemented by direct current measurement and disconnection of the drive signals to the switching power transistors.

Accordingly, by the present invention is achieved a (integral or proportional integral) controller which controls close to zero reactive power in the parallel resonant current-driven inductive coupler. Since the drive control delivers approximately constant current due to an inductor in the supply of power, this results in that one controls reactive power to close to zero (square driving current 90 degrees displaced multiplied with the primary drive voltage over input to the inductive coupler). Spice simulations performed by the applicant, e.g. as shown in Fig. 6, confirm that the control strategy according to the present invention results in low switch transients and loss, even if there are some higher harmonics present.

The control method according to the present invention is thus based on adjusting reactive power in to the parallel resonant transformer to close to zero, and that this implicit implies ZVS (zero voltage switching), i.e. which is a novel and inventive basic principle in relation to prior art control methods for inductive couplers with current drive ZVS.

The solution according to the present invention is especially favorable when one have a structure of the driving electronics where a push-pull constant current driving (center tap design transformer) is used. The current driving can also be performed by utilizing a full bridge on the driving side, and not have an intermediate outlet on the primary side of the inductive coupler. The latter solution requires a more complicated driving electronics, but can give some lower copper loss in the inductive coupler and makes the design of the primary coil some simpler, at the same time as one holds the voltage over the switching power transistors lower. A drawback is however that the losses in the switching power transistors will be higher.

The present invention is not limited to inductive couplers with constant current driving as mentioned above, i.e. square shape of the current after switching.

If the current has another shape, the driving voltage and quadrature of the driving current must be multiplied together in real time instead of performing the multiplication only by a sign change for the current. This can best be made in a FPGA (Field-programmable gate array) or ASIC (application-specific integrated circuit) due to the speed requirements.

The present invention further also has the advantage that it eliminates the known problem of prior art with chaotic oscillation in freely oscillating couplers in case that one has a coupling factor which results in supercritical coupling (dual resonance frequencies) between primary and secondary side. This due to the drive control according to the present invention can be set to react relatively slowly so that one only get a slow “wandering” in the interval between the two frequencies and thus gets improved triggering signals as regards loss in the switching power transistors.

A further advantage with the present invention is that it provides a solution where one is getting rid of as much magnetizing current from the inductive coupler as possible, due to both primary and secondary side are run in parallel resonance and that the reactive current is compensated for with an outer capacitor on each side of the inductive coupler.

The present invention is further based on a current driving design with strong resonance, as opposite to some prior art solutions, where the controller adjusts electrical capacitance the present invention is based on the use of a symmetrical primary and secondary side which have approximately the same resonance frequency at both sides independent of the size of the air gap. In the present invention the control involves adaption to the natural resonance frequency between the inductance in the coupler and the adjacent capacitors. Tuning of inductance or capacitance result in increased loss in the switching power transistors as a part of the control. In the present invention the field path is short, and the direct radiation is low even if the magnetic field in the path is significant, and one will meet the requirements for EMI (electromagnetic interference) without need for utilizing frequencies reserved for wireless transfer of power.

An advantage with the present invention is that it is adapted for the use of parallel resonance and ZVS which is required for applications as inductive coupler, which provides a more stable voltage output without control, as well as it is robust for overvoltage at intermittent loss of (wireless) feedback from the secondary side. This will simplify the design of the inductive coupler and is particularly attractive in applications where the voltage from the secondary side has to be converted to a multitude of non-standard voltage levels as often found in instrumentation and data equipment. This will also ease the design of the inductive coupler concerning overvoltage protection.

A further advantage is that the present invention provides a simple hardware function for both analog and digital implementation.

A further advantage of the present invention is that it provides improved noiseless observation of the triggering point of the switching power transistors by utilizing the entire time function of the voltage in calculation of the switching frequency/triggering point, compared to use of an advanced solution based on the state equations. This will minimize the influence from possible very high harmonics which can lie in the level one has chosen to set the voltage levels in the state equations. The net result of this is a more accurate triggering and reduced switching loss compared to prior art solutions.

A further advantage with the present invention is that it is provided a solution which will function optimally also when the input voltage contains significant ripple. This ripple can originate from a multiphase AC rectifier or moderately capacitor filtered voltage from a single phase rectifier, thus easily conforming to regulations for power factor on the AC-input. The trigger controller will track the changes in input voltage given by the AC-ripple thus providing a high efficiency also in high AC-ripple situations.

Further preferable features and advantageous details of the present invention will appear from the following example description, claims and attached drawings.

Example

The present invention will below be described in further detail with references to the attached drawings, where:

Figure 1 is a principle drawing of transfer of magnetic energy over an air gap,

Figure 2 is a linear model for a parallel resonant inductive coupler having tuned primary and secondary sides,

Figure 3 is a principle drawing for drive control of a parallel resonant current-driven inductive coupler according to the present invention,

Figure 4 is a circuit diagram of an example embodiment according to the present invention,

Figure 5 shows the same as Figure 4 but implemented with a full bridge drive, and

Figure 6 is a simulation result showing drive current and voltages at switching power transistors for an inductive coupler based on the embodiment in Figure 4, after that the controller has come to steady state.

Reference is first made to Figure 1 which is a principle drawing of transfer of magnetic energy over an air gap by means of rotation symmetric pot core which is the basic principle the present invention seeks to improve.

In Figure 2 it is shown a principle drawing of a linear model for power transfer in a transformer, where:

Rlop: Resistance, - copper loss on the primary side; Rlos: Resistance, - copper loss on the secondary side; Lsp: Inductance, spread primary; Lss: Inductance, leakage, secondary; Ri: Resistance, parallel loss in ferrite core; Ls: Inductance, idle magnetization; Rl: load resistance; Vp: primary voltage. Cp, Cs: the primary and secondary resonance capacitors used for reduction of magnetizing current.

Ls is reduced when the air gap between the parts is increased. It will then run a considerable current through Ls which increases the copper loss in Rlop. Lsp and Lss also increase somewhat when the air gap increases. This is caused by wider flux paths back in the air gap outside the coils when the air gap increases (scattered flux). The increase of Lsp and Lss sets a limit to transfer of power in the cases where the air gap is large.

Calculations on the circuit in Figure 2 without the capacitor Cs show that maximum power is transferred to Rl when this load is equal to the complex conjugated of Zi, where Zi is the inner complex impedance, seen from the secondary side.

In other words, the resonance between inner L and outer C will theoretically maximize transferred power to Rl. Cs is chosen to be at this value at nominal air gap and drive frequency. To keep Zi as low as possible to maximize power transfer this will result in a low value also of Ls, and hence high magnetizing current flowing trough Ls. This makes it favorable to reduce the currents running through switching power transistors by strong tuning of the transformer by the capacitors Cp and Cs. The limit for this tuning is given by balancing of copper and magnetic core loss with switching power transistor switching loss. The loss in capacitors Cp and Cs can usually be neglected.

Further, simulations show that the reactive drive current at Vp increases nearly linearly with the frequency, which according to the present invention will be utilized for control of frequency to close to zero reactive current dynamically.

Reference is now made to Figure 3, which is a principle drawing for drive control for a parallel resonant current-driven inductive coupler according to the present invention, only showing the primary side of the resonant inductive coupler.

The present invention is based on a drive control including an electronic oscillator 100, such as a VCO (Voltage-controlled Oscillator) which provides a square-shaped driving voltage. In an alternative embodiment the electronic oscillator is implemented based on a SOC (System on chip) with a fast high resolution built-in programmable PWM (Pulse-width modulation). For the further description it will be referred to the VCO 100 as electronic oscillator. The square-shaped voltage from the VCO 100 is supplied to a current switching driver 110, including switching power transistors 111a-b, which again is connected to a resonant transformer 120, which has an air gap dependent resonance frequency in relation to the secondary side.

The drive control further includes a phase displace unit 130, e.g. in the form of a delay element, for phase displacing the square form transformer 120 driving current from the VCO 100 with 90 degrees.

The drive control further includes a multiplying unit 140, arranged for multiplying measured driving voltage at the resonant transformer 120 with the phase displaced current from the phase displace unit 130, where the product (reactive power) is supplied to a controller 150 which integrates the product of the multiplication for control of the frequency via the VCO 100.

Figure 4 shows parts of a possible electrical implementation of the parallel resonant current-driven inductive coupler according to the present invention. A DC power source 200 supplies power through an inductor 210. The inductance of the inductor 210 is so high that the supply current to a transformer 120 midpoint is predominantly constant at any time. The primary side 121 of the transformer 120 has a center tap 122 feeding on a primary coil 123. A primary resonance capacitor 124 of the transformer 120 is according to the present invention preferably formed by two serially coupled capacitors 124a and 124b, and is terminated at the primary coil 123 center tap 122. By the use of two serially coupled capacitors 124a-b achieved is a solution that damps spikes in the switching given by transformer leakage inductance between the primary coil halves. The switching power transistors 111a-b of the current switching driver 110 are e.g. fast GaN (Gallium nitride) transistors operating with a small ”break before make” time interval to avoid current flow between the switching power transistors 111a-b during switching. The “brake before make” function can e.g. be implemented by the current switching driver 110 using an analog delay function. This analog delay function is closely matched to the switching power transistors 111a-b switch off time.

In addition it is preferably arranged a snubber network 220 in parallel with the inductor 210 which is arranged for avoiding voltage increase on the switching power transistors 111a-b during the brake before make transition period between the driving of the switching power transistors 111a-b.

For measuring of the primary drive voltage the drive control according to the present invention further includes a differential amplifier 230 arranged to measure the voltage time-function across the primary drive coil 123.

The multiplication with the phase displaced drive current from the phase delay unit 130 is e.g. performed by a multiplying unit 140 including a switch 141 performing a sign shift on the 90 Deg phase shifted current drive signal to the switching power transistors 111a-b. This phase delay can for instance be implemented by operating at the double VCO-frequency and use of some simple logic not detailed in Figure 4.

The drive control according to the present invention can further include adding an offset 240 to the computed reactive power. This offset 240 can be used to marginally adjust the already found optimal triggering point by the method described herein. This can be performed during factory testing. Another possibility is to perform this optimization continuously by adding a very small time varying offset 240 generated by a perturbation method driven by the temperature of the switching power transistors 111a-b. The long term very optimal trig point can then be found using a standard numerical search method. This optimization will adjust for average drive conditions like average drive voltage, average power delivery, average size of air gap and ageing of components. This digital function can preferably be implemented as a part of a digital supervision unit 400 (Figures 4 and 5) for the inductive coupler. With the described drive control design the switching will take place at close to zero voltage (ZVS-design) over the switching power transistors 111a-b. There is near ideal symmetry between the two switch sides, and we assume that the secondary load is also symmetric. The switching for the two switching power transistors 111a-b will then also be symmetric so that ideal time between switchings will be equal or approximately equal.

Figure 6 shows a typical recording of voltage on the switching power transistors 111a-b (curves denoted with 1 and 2 in the figure), and a recording of total drive current (curve denoted 3 in the figure), based on a Spice simulation with some actual components for an inductive coupler according to the present invention at 100-500 W power level. The recording in Figure 6 was performed after the drive control (control loop) had come to stationary state. Note from the simulation that switching occurs at close to zero voltage on the switching power transistors 111a-b.

Modifications

The switching power transistor design based on a half bridge as shown in Fig. 4 with midpoint tapping of the primary coil 123 is preferable at lower drive voltages, say below 50 V, since the maximum voltage on the switching power transistors will be well above two times the supply voltage.

For high input voltage the use of a full bridge design for the switching power transistors is preferred, as shown in Figure 5. The switching power transistor loss will be lower than in a half bridge design than in a full bridge even if the primary coil 123 will be slightly less efficient. The inductor 210 in Fig. 4 with the snubber network 220 will then in the same way be arranged next to the power source 200 also for a full bridge design. The function of the full bridge circuit should be the same concerning trigger control as for the half bridge version in Figure 4.

Claims

1. Method for control of a parallel resonant current-driven inductive coupler having a primary side and secondary side formed by a magnetic E, U or pot core, the primary and secondary sides being separated by an air gap, the inductive coupler being powered by a power source (200) and being controlled by a drive control, the drive control including an electronic oscillator (100), current switching driver (110) including switching power transistors, controller (150) and primary side of a resonant transformer (120), **characterized by** control of driving frequency of the inductive coupler in such a way that reactive power from the drive control in to the inductive coupler becomes close to zero, and utilizing the control of the close to zero reactive power to continuously minimizing switch-on voltage in the switching power transistors as they connect and disconnect, and thus reducing switching loss.

2. Method according to claim 1, **characterized by** measuring reactive power with sign supplied to primary side of the inductive coupler, and using the controller (150) for adjusting the driving frequency to close to zero reactive power.

3. Method according to claim 2, **characterized by** phase displacing the driving current measurement with 90 degrees by means of a phase displace unit (130).

4. Method according to claims 2-3, **characterized by** performing the measurements of reactive power by multiplying the phase displaced driving current with primary voltage and averaging/integrating this product by means of analog or digital processing.

5. Method according to claim 4, **characterized by** adding proportional effect in addition to pure integral effect in the drive control to achieve a faster control to correct level and fast adaptation to changing loads or ripple in the supply voltage.

6. Method according to claims 2-4, **characterized by** adding a fixed offset to the measured reactive power for fine tuning of switching frequency/triggering point of the switching power transistors to minimize switching loss in the switching power transistors (110).

7. Method according to claim 6, **characterized by** that long term optimization of the offset to the measured reactive power is found by continuously searching for a temperature minimum on the switching power transistors by pertubating small deviations on said offset by use of a numerical search method.

8. Method according to any one of the preceding claims, **characterized by** determining initial value of the frequency in the controller (150), based on:

- last used quality controlled best initial value,

- a measurement of resonance frequency performed at low current-voltage-amplitudes as part of a turn-on procedure for the inductive coupler,

- initial frequency at nominal distance between primary and secondary core of the inductive coupler, or

- a measurement of input voltage from the power source (200).

9. Method according to claim 8, **characterized by** determining the initial value of the frequency in the controller (150) based on a measurement of input voltage from the power source (200) and use this for correction of the measured resonance frequency at low drive amplitude.

10. Parallel resonant current-driven inductive coupler having a primary side and secondary side formed by a magnetic E, U or pot core, the primary and secondary sides being separated by an air gap, the inductive coupler being powered by a power source (200) and being controlled by a drive control, the drive control including an electronic oscillator (100), current switching driver (110) including switching power transistors, controller (150) and primary side of a resonant transformer (120), **characterized in** that the drive control being arranged for control of driving frequency of the inductive coupler in such a way that reactive power from drive control in to the inductive coupler becomes close to zero, and control of the close to zero reactive power to continuously minimizing switch-on voltage in the switching power transistors as they connect and disconnect for reducing switching loss.

11. Parallel resonant current-driven inductive coupler according to claim 10, **characterized in** that the drive control includes a phase displace unit (130) for phase displacing driving current from the electronic oscillator (100).

12. Parallel resonant current-driven inductive coupler according to claim 10, **characterized in** that drive control includes a differential amplifier (230) measuring primary voltage by measuring voltage time function across primary drive coil (123).

13. Parallel resonant current-driven inductive coupler according to claims 11-12, **characterized in** that the drive control includes a multiplying unit (140) arranged for multiplication of the phase

displaced driving current with the measured primary voltage providing a measure for reactive power.

14. Parallel resonant current-driven inductive coupler according to claims 10-13, **characterized in** that the drive control includes an integral or proportional integral controller (150), the controller (150) being arranged for integration of the product of the multiplication of the phase displaced driving current and the primary voltage for control of the frequency via the electronic oscillator (100).

15. Parallel resonant current-driven inductive coupler according to claim 10, **characterized in** that an inductor (210) is arranged between the power source (200) and transformer (120).

16. Parallel resonant current-driven inductive coupler according to claim 15, **characterized in** that a snubber network (220) is arranged in parallel with the inductor (210).

17. Parallel resonant current-driven inductive coupler according to claim 15, **characterized in** that a primary inductor (123) at primary side (121) of the transformer (120) is provided with a center tap (122) for supply of power via the inductor (210).

18. Parallel resonant current-driven inductive coupler according to claim 17, **characterized in** that a primary resonance capacitor (124) of the transformer (120) is formed by two serially coupled capacitors (124a-b), and is terminated at the primary coil (123) center tap (122).

19. Parallel resonant current-driven inductive coupler according to claim 10, **characterized in** that the current switching driver (110) is provided with an analog delay function providing a "break before make" function for the switching power transistors.

20. Parallel resonant current-driven inductive coupler according to claim 13, **characterized in** that the drive control includes an input for adding an offset (240) to the computed reactive power.

21. Parallel resonant current-driven inductive coupler according to claim 20, **characterized in** that the inductive coupler includes a supervision unit (400) arranged for adding a time varying offset (240) generated by a perturbation method driven by temperature of the switching power transistors.

22. Parallel resonant current-driven inductive coupler according to claims 15-16, **characterized in** that the transformer (120) is supplied with power via the inductor (210) at endpoints of the primary coil (123).

23. Parallel resonant current-driven inductive coupler according to claim 17, **characterized in** that the switching power transistors are arranged in a half-bridge design.

24. Parallel resonant current-driven inductive coupler according to claim 22, **characterized in** that the switching power transistors are arranged in a full-bridge design.

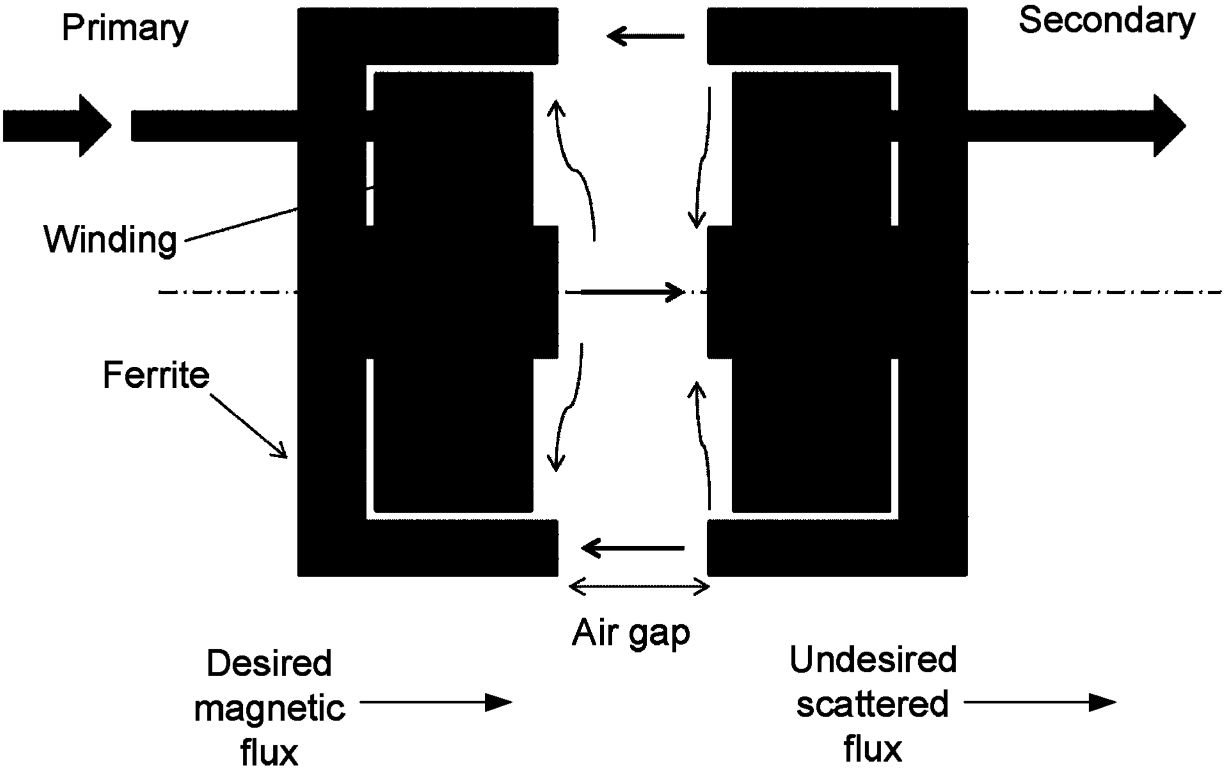

Primary
Secondary
Winding
Ferrite
Air gap
Desired magnetic flux
Undesired scattered flux

Fig. 1.

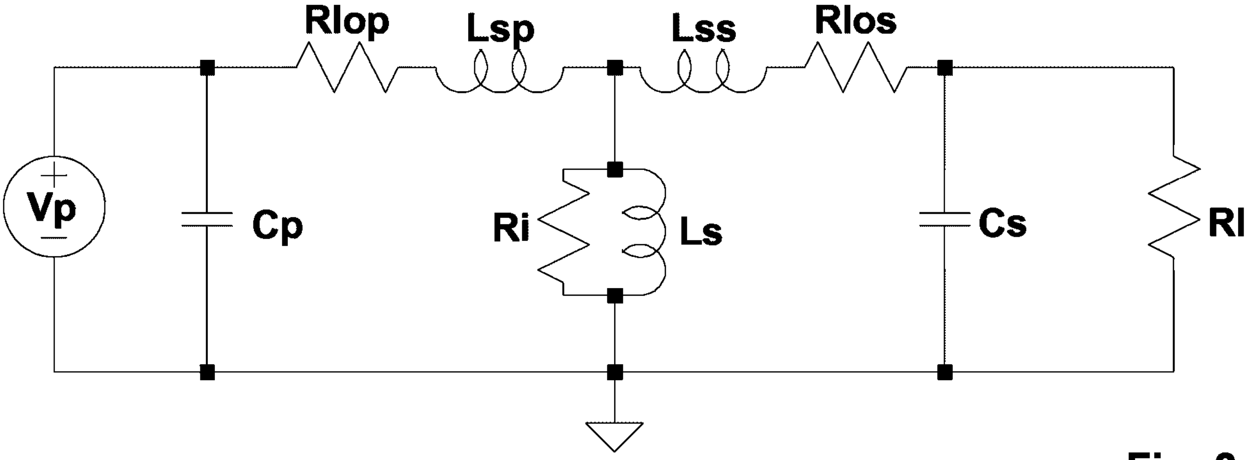

Rlop
Lsp
Lss
Rlos
Vp
Cp
Ri
Ls
Cs
Rl

Fig. 2.

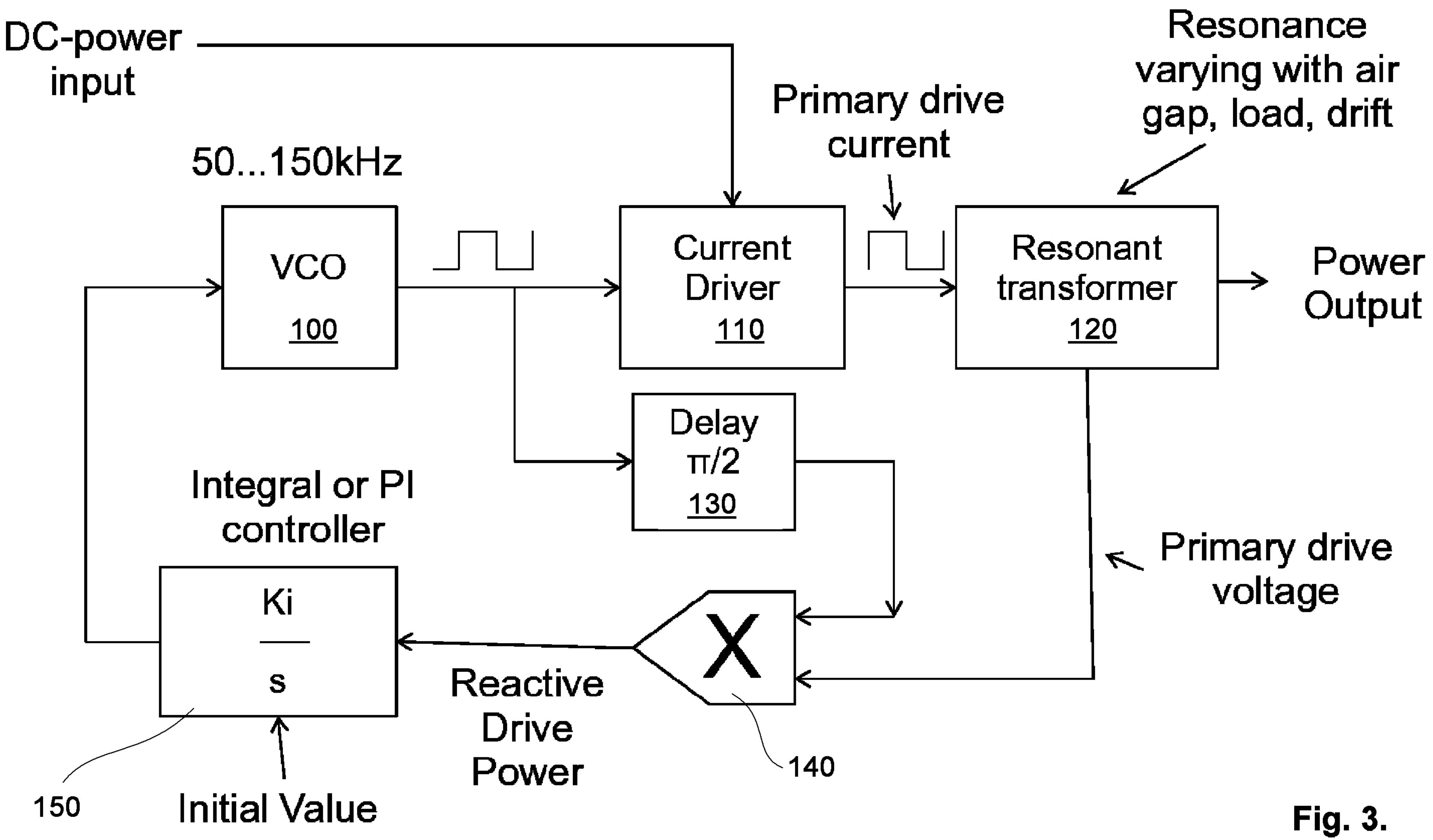

DC-power input
50...150kHz
VCO
100
Current Driver
110
Primary drive current
Resonance varying with air gap, load, drift
Resonant transformer
120
Power Output
Delay
π/2
130
Integral or PI controller
Ki
s
Primary drive voltage
X
Reactive Drive Power
140
150
Initial Value

Fig. 3.

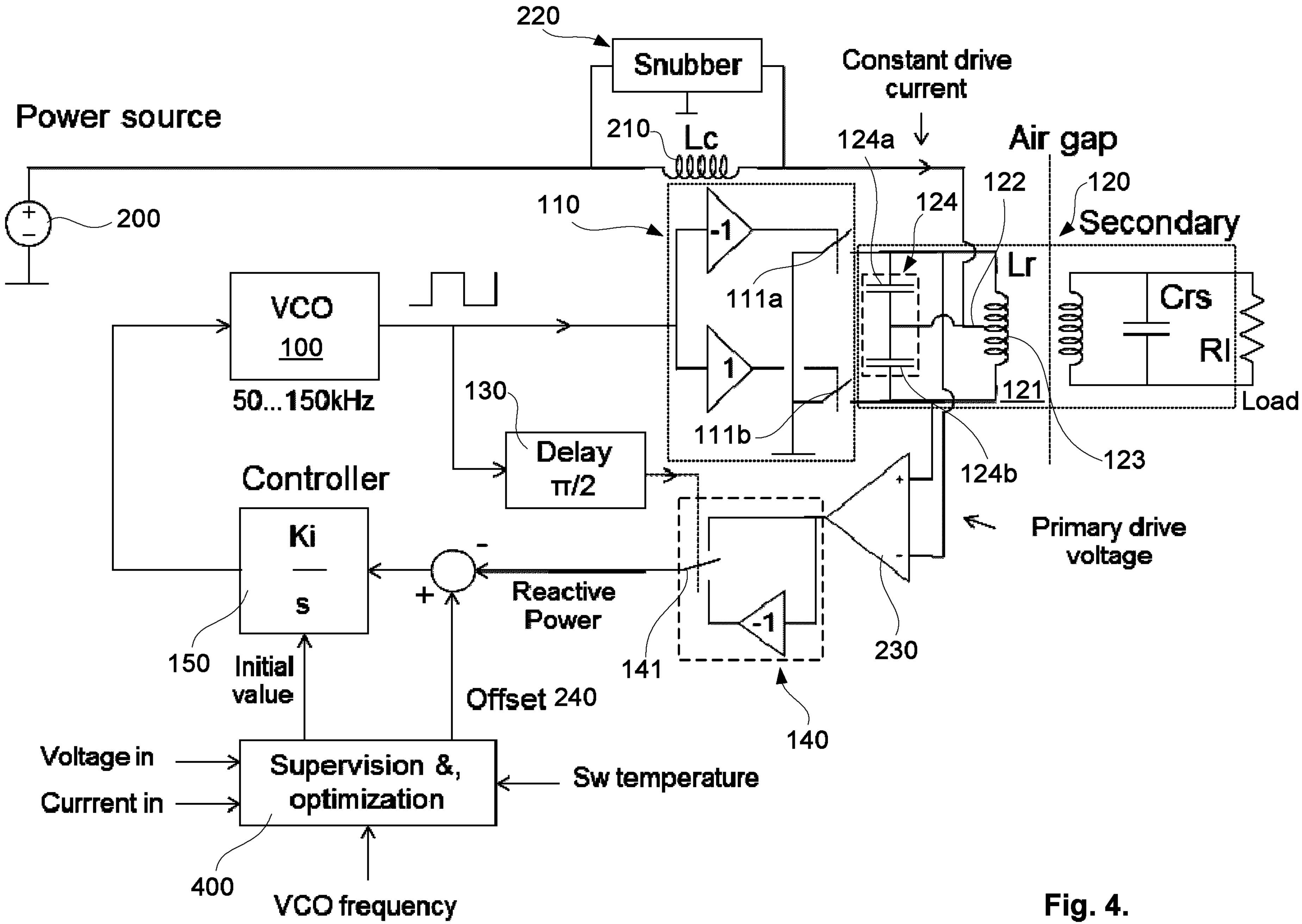

220
Snubber
Power source
210
Lc
Constant drive current
124a
Air gap
200
110
124
122
120
Secondary
-1
Lr
VCO
100
111a
Crs
1
Rl
50...150kHz
130
121
Load
111b
Delay
π/2
124b
123
Controller
+
-
Ki
s
Primary drive voltage
-
+
Reactive Power
-1
230
150
Initial value
141
Offset 240
140
Voltage in
Supervision &, optimization
Sw temperature
Currrent in
400
VCO frequency

Fig. 4.

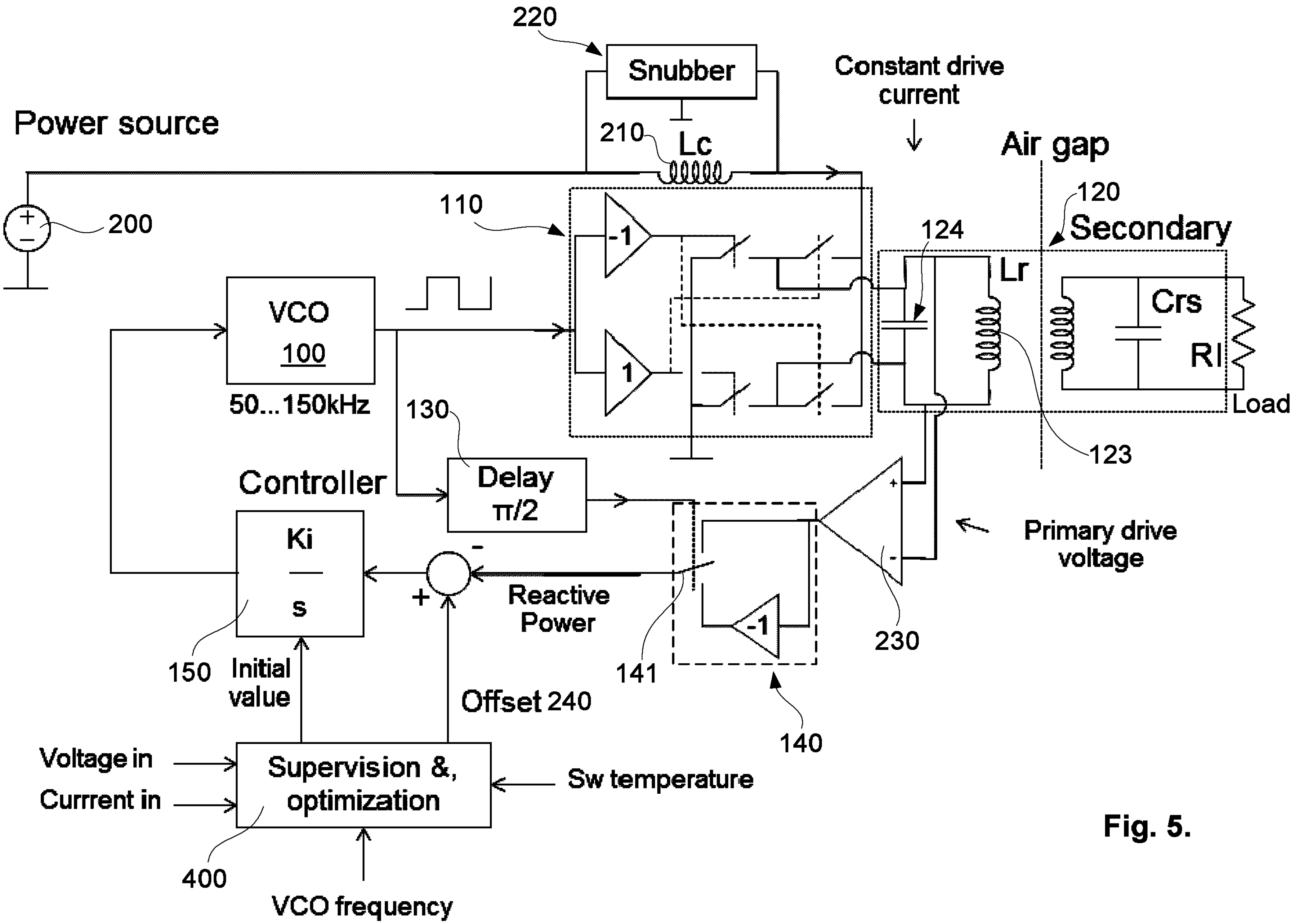
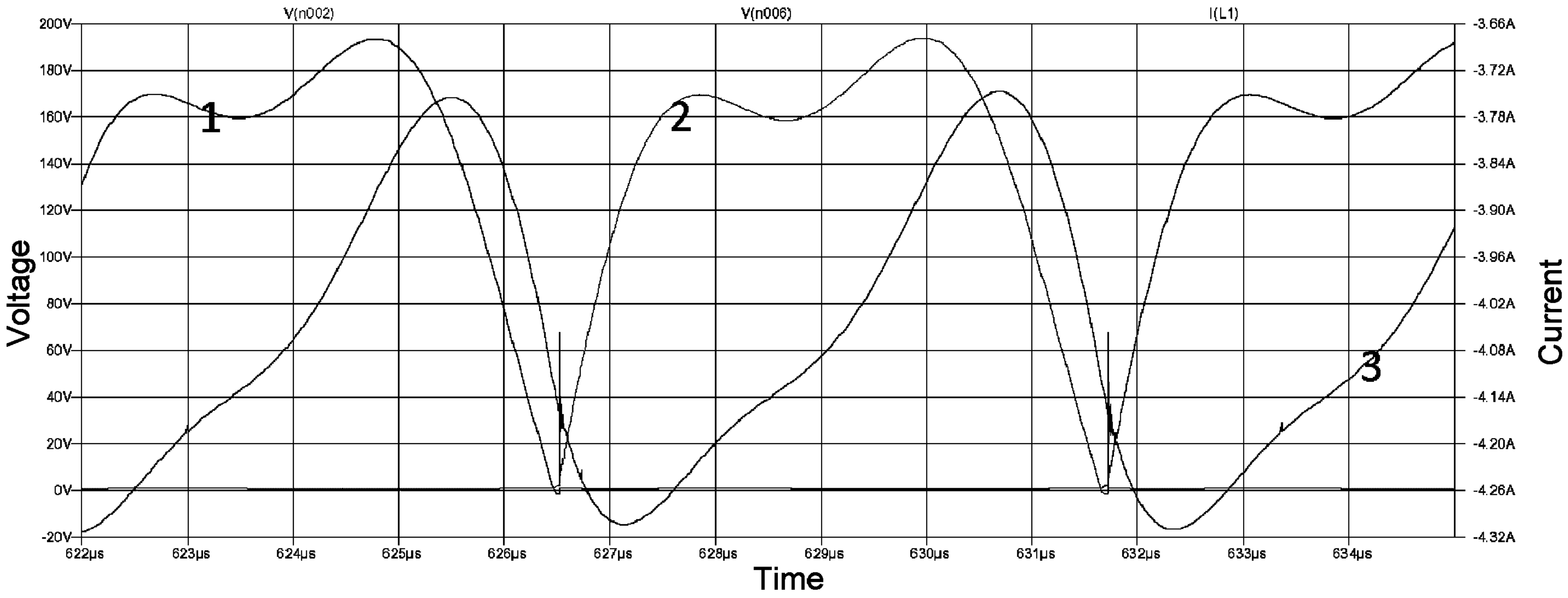

220
Snubber
Constant drive
current
Power source
210
Lc
Air gap
120
Secondary
200
110
124
Lr
VCO
100
Crs
Rl
-1
1
50...150kHz
Load
130
Delay
π/2
123
Controller
Ki
s
Primary drive
voltage
-
+
Reactive
Power
-1
230
150
Initial
value
141
Offset 240
140
Voltage in
Currrent in
Supervision &,
optimization
Sw temperature
400
VCO frequency

Fig. 5.



1,2 – voltages at driving switches/transistors 111a and 111b, respectively.
3 – Drive current.

Fig. 6.