Resonant power converter with dead-time control of synchronous rectification circuit

The invention relates in a first aspect to a resonant power converter comprising a synchronous rectifier for supplying a DC output voltage. The synchronous rectifier is configured for alternatingly connecting a resonant output voltage to positive and negative DC output nodes via first and second semiconductor switches, respectively, separated by intervening dead-time periods in accordance with first and second rectification control signals. A dead-time controller is coupled to the resonant output voltage or the resonant input voltage and configured for adaptively adjusting lengths of the dead-time periods via the first and second rectification control signals.

Resonant power converter comprising adaptive dead-time control.

The invention relates in a first aspect to a resonant power converter comprising: a first power supply rail for receipt of a positive DC supply voltage and a second power supply rail for receipt of a negative DC supply voltage. The resonant power converter comprises a resonant network with an input terminal for receipt of a resonant input voltage from a driver circuit. The driver circuit is configured for alternatingly pulling the resonant input voltage towards the positive and negative DC supply voltages via first and second semiconductor switches, respectively, separated by intervening dead-time periods in accordance with one or more driver control signals. A dead-time controller is configured to adaptively adjusting the dead-time periods based on the resonant input voltage.
Analysis of bi-directional piezoelectric-based converters for zero-voltage switching operation

This paper deals with a thorough analysis of zero-voltage switching especially for bi-directional, inductorless, piezoelectric transformer-based switch-mode power supplies with a half-bridge topology. Practically, obtaining zero-voltage switching for all of the switches in a bi-directional piezoelectric power converter is a difficult task. However, the analysis in this work will be convenient for overcoming this challenge. The analysis defines the zero-voltage region indicating the operating points whether or not soft switching can be met over the switching frequency and load range. For the first time, a comprehensive analysis is provided, which can be used as a design guideline for applying control techniques in order to drive switches in piezoelectric transformer-based converters. This study further conveys the proposed method to the region where all the switches can obtain soft switching. Moreover, the analysis can be applied to other types of resonant converters with or without piezoelectric transformers. Experimental and simulation results are provided, verifying the performed analysis.

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A new method is implemented in designing of self-oscillating loop for driving piezoelectric transformers. The implemented method is based on combining both analog and digital control systems. Digitized delay, or digitized phase shift through the self-oscillating loop results in a very precise frequency control and ensures an optimum operation of the piezoelectric transformer in terms of voltage gain and efficiency. In this work, additional time delay is implemented digitally for the first time through 16 bit digital-to-analog converter to the self-oscillating loop. Delay control setpoints updates at a rate of 417 kHz. This allows the control loop to dynamically follow frequency changes of the transformer in each resonant cycle. The operation principle behind self-oscillating is discussed in this paper. Moreover, experimental results are reported.
Dynamic optimum dead time in piezoelectric transformer-based switch-mode power supplies
Soft switching is required to attain high efficiency in high-frequency power converters. Piezoelectric transformer-based converters can benefit from soft switching in terms of significantly diminished switching losses and stresses. Adequate dead time is needed in order to deliver sufficient energy to charge and discharge the input capacitance of piezoelectric transformers in order to achieve zero-voltage switching. This paper proposes a method for detecting the optimum dead time in piezoelectric transformer-based switch-mode power supplies. The provision of sufficient dead time in every cycle of the switching period results in the quick start up of resonant current inside the transformer. The new method is implemented by dynamically detecting the optimum dead time for each resonant cycle and results in reduced energy loss, and consequently, increased efficiency in the converter during initialization time and steady-state operation.

The theory of optimum dead time operation is also discussed in this paper. Experimental results and simulation are provided to show the implementation of the concept.

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Inductorless bi-directional piezoelectric transformer-based converters: Design and control considerations.

Piezoelectric transformers were introduced to the world in 1954 and turned into the best alternative for replacing the magnetic transformers. Recently, the development of research on piezoelectric-based switch-mode power supplies has gathered pace and led to extensive research development. However, this brings an open area for conducting further research which has been subject of this project. The research on this type of power converters are progressive but still very new in the technology to become a successful commercial product. The unique characteristics of piezoelectric transformers i.e. low electromagnetic interference, compact, light, high power density and low cost allows for promising market in the near future. The piezoelectric transformer technology has the potential to be used in various applications e.g. motor driver for magnetic resonance imaging scans, the electronic ballast for fluorescent lamps, backlight for LCD displays in notebook computers. Piezoelectric ceramic devices vibrate at their mechanical resonance. The operating principle of the piezoelectric transformers is based on electromechanical energy conversion. 

There is electromechanical coupling between the primary- and secondaryside of piezoeo ceramic, where the primary acts as a piezoelectric actuator and the secondary acts as a piezoelectric transducer. Therefore, piezoelectric transformers can be used as a replacement of resonant circuits in the power converters. This introduces piezoelectric transformers as applicable candidates for applications that have a high sensitivity to electromagnetic interference. The nonmagnetic bidirectional piezoelectric transformer-based switch-mode power supplies as the topic of this thesis is one of these applications. The dissertation presents the design, control and implementation of inductorless switch-mode power supplies employing piezoelectric transformers. The main focus of this research is on the functionality of the piezoelectric transformer-based power converters and applying control techniques in order to exploit advantages of the piezoelectric transformers for the power converters. Therefore, the research is devoted to stepwise development of all parts of the inductorless piezoelectric transformer-based switch-mode power supply. The developments have been mainly on the transformer design for internal resonant current sensing, increasing their capability in transferring energy and soft switching, following changes of the piezoelectric transformer in order to control operation of the piezoelectric transformer for the benefit of the power converters, digitizing control system, applying new control techniques compared to previously applied methods, implementing dynamic optimum dead time detector applicable for switch-mode power supplies, optimum phase detector, bi-directional wide bandwidth current sensor and a comprehensive analysis of piezoelectric transformer-based switch-mode power supplies for zero-voltage switching, where all finalized with improving the unidirectional topology with resistive and passive rectifiers as well as bi-directional topology with a capacitive load. The investigation of the piezoelectric transformers in terms of sensing the resonant current and increasing their capability of handling high power was carried out in collaboration with the project’s industry partner. New samples of piezoelectric transformers were designed, fabricated and tested. Experiments showed promising results on sensing the resonant current, but could not be used for the control system in this research since having both sensing electrode and zero-voltage switching could not be obtained in one package. Moreover, a progress of increasing power capability of piezoelectric transformer’s was a step forward to overcome the limitations in the technology of the piezoelectric transformers. Operation of unidirectional topology deals with finding solutions for advance control of piezoelectric transformers in terms of operating under various load, frequency and temperature changes. In order to follow changes in the characteristic of the transformers and control their operation, a digitized self-oscillating loop designed and implemented. The main advantage of the digitized self-oscillating loop is that the time delay inside the loop is able to be changed with the resolution of 1 ns. This provides the possibility of sweeping the operating point on the characteristic over the frequency range by very fine frequency steps where considerable changes in the output voltage of the transformer are visible. This is done by shifting the gate voltages of the switches versus the resonant current. Having access to the mechanical resonance of the piezoelectric material inside the piezoelectric transformer, known as "resonant current" in its equivalent electrical circuit, simplifies the control system of the entire converter. Therefore, attempts were made to find solutions for sensing the resonant current over the whole...
or part of the switching time period. The first approach was to design a piezoelectric transformer with feedback to sense the mechanical resonance. The second approach was to design a current sensor for measuring the input current to the transformer which is equal to the resonant current during the on time of the switches. The second approach requires a wide bandwidth bi-directional current sensor to be able to operate in the presence of the high common-mode voltage. Part of this research allocates to implementation of the current sensor. A new method for optimizing the dead time in every switching cycle is proposed. The dynamic optimum dead time detector starts to detect the time point where the switching voltage reaches the rails or passes through its local maxima. This results in the minimum or the optimum dead time between the switching transitions and further expanding the duty cycle of the switches in order to provide more energy to the converter. The advantage will be reduction of the start-up time in the converter and the switching losses.

The main achievement of this research is a new implementation of bi-directional piezoelectric transformer-based switch-mode power supply with two configurations. This implementation is applicable for the control system of switch-mode power supplies, specially resonant power converters. Finally, the outcome of the research is implemented and tested in the final prototype with combining all the designed sub-circuits to investigate the bi-directional functionality of the power supply, which resulted in a successful outcome in the control techniques.

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**Power enhancement of piezoelectric transformers for power supplies.**
This paper studies power enhancement of piezoelectric transformers to be used in inductorless, half-bridge, piezoelectric-based switch mode power supplies for driving a piezo actuator motor system in a high strength magnetic environment for magnetic resonance imaging and computed tomography applications. A new multi element-piezoelectric transformer solution is proposed along with a dual mode piezo transformer, providing power scaling and potentially improving the internal heat-up of a high power piezo transformer system.

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**Bi-directional high-side current sense circuit for switch mode power supplies**
In order to control a power supply using piezoelectric transformer, AC current in the transformer needs to be measured. Due to the control strategy it is necessary to measure amplitude, phase angle and zero crossing of this current. In some
applications there is common ground between primary and secondary sides of the transformer which is internally implemented inside the transformer. Therefore, current must be measured from the high voltage line in the presence of high input switching voltage. This paper proposes a resistive current sensing circuit based on discrete components useful for input voltage on the order of 200 V. The bandwidth is at least 200 kHz to allow fundamental frequency detection of piezoelectric transformers in use.

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**Nonmagnetic driver for piezoelectric actuators**
Piezoelectric actuator drive aims to enable reliable motor performance in strong magnetic fields for magnetic resonance imaging and computed tomography treatment tables. There are technical limitations in operation of these motors and drive systems related to magnetic interference. Piezoelectric actuator drive is the only form-fit continuous drive solution currently available for the development of high performance nonmagnetic motors. In this research focus will be on the non magnetic compact high efficiency driver for the piezo actuators and on employing energy recovery from the capacitive actuators. Therefore, piezoelectric transformer-based power converters are used for driving piezoelectric actuator drive motor in the presence of high electromagnetic field.

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**State-of-the-art piezoelectric transformer-based switch mode power supplies**
Inductorless switch mode power supplies based on piezoelectric transformers are used to replace conventional transformers in high power density switch mode power supplies. Even though piezoelectric-based converters exhibit a high degree of nonlinearity, it is desirable to use piezoelectric transformers due to their smaller size, lighter weight, lower electromagnetic interference, higher power density, higher efficiency, and lower cost. Moreover, PTs allow converters to operate in high switching frequencies and by obtaining soft switching condition, switching losses will decrease. This paper discusses power supplies with the trend evaluation of piezoelectric transformer-based converter topologies and control methods. The challenges of piezoelectric transformers regarding soft switching capability and nonlinearity are addressed. This paper can be used as a guideline for choosing a proper topology of piezoelectric-based switch mode power supply and a control method for the required application.