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A Comprehensive Review: Topology, Modeling and Control Techniques of Resonant Converter for Electric Vehicle Applications

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Abstract: ***This paper proposes the comprehensive review on the different resonant converter topologies, different modelling techniques, and different control techniques are being used in electric vehicle application. This paper also discusses the merits and demerits of different modulation/control techniques. The performance of variable frequency control technique can be improvised using SSPM is discussed in this paper. Optimal projectory control method has a quick transient response than SSPSM followed by SSOC, then PSM, and finally by VF controller are reviewed in detail in this study. Cyclic averaging is an accurate alternative method for state variable, this approach is used for time domain analysis of resonant dc-dc converter has been emphasized in this paper. Reverberation would be beneficial when series and parallel resonance converters combined are explained in this paper. LLC topology would be best suitable for electric vehicle applications are discussed and structure of the resonant converters, power efficiency, compatibility and its suitable applications are presented in this paper. A detailed study of modelling techniques to address the increasing demand for electric vehicles are presented.***

Keywords: Electric Vehicle, Modelling, Control Techniques

I. INTRODUCTION

Resonant converters are widely used in various applications mainly includes photovoltaic systems, lighting drivers, EV charging, LEDs, liquid crystal displays and TV power supplies [1].

The rapid increase of resonant converter is mainly due to its reduced electromagnetic interference (EMI), great efficiency, low voltage stress, high energy density and high frequency of operation, because of the increased demand, researcher to study on different techniques. With the increasing demand, there is a concomitant growth in demand for resonant converters for electric vehicle applications. Hence, resonant converters are used for this purpose, can be improved as better components and are being developed, this stimulates researchers to conduct study on a improved design, modelling, and control methods.

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II. STRUCTURE OF RESONANT CONVERTER

Resonant converters have two full bridges, in charging mode, the primary functions as a high frequency inverter, and secondary function performs rectification [1], [2].

The input source's dc side transfers the electricity to the batteries in charging mode and then returned to the dc bus in method of discharge. The resonant tank and transformer have been installed at the middle of two full bridges as seen in Fig.1.

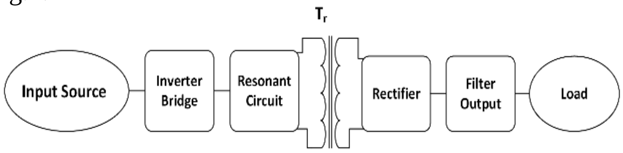

Fig.1. Structure of resonant converter.

III. CATEGORIES OF RESONANT CONVERTER

Resonant converters may be divided into series converter, parallel converter, series-parallel resonant. It can be further separated into LCC, CLLC, LLC, LCL-T converter, and many others [2]-[6]. It can be classified based on topologies, resonant converters with half bridges, full bridges, and push pulls. The resonating element in a resonating inductor Lr will be connected to the resonating capacitor Cr in series as shown in Fig.2.

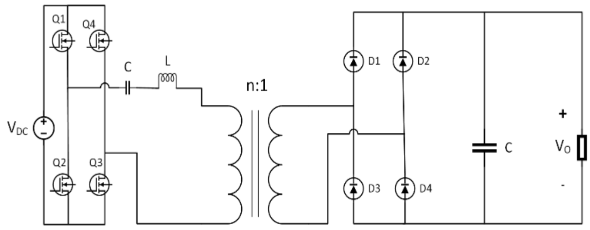

Fig.2. Circuit diagram of resonant converter in series

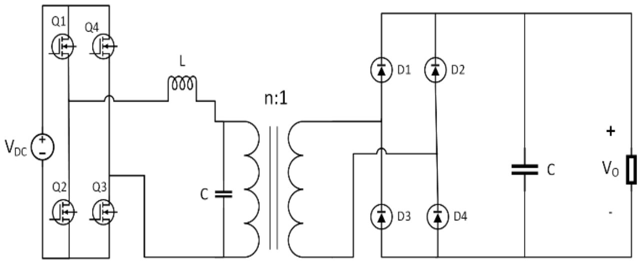

Fig.3. Circuit diagram of resonant converter in parallel

In parallel resonant converter the resonating inductor Lr, resonating capacitor Cr connected in parallel as seen in Fig.3.

In series-parallel resonance converter consists of three components, each of which has two options, two inductors one-capacitor or one-inductor two capacitors, Additional inductance will be introduced to attain resonance. To obtain the reverberation, series and parallel resonance converters combined would be beneficial. In LCC, resonant converter has two capacitors and one inductor as resonating parameters, it is capable of regulating the resultant voltage by connecting capacitor in parallel as shown in Fig.4

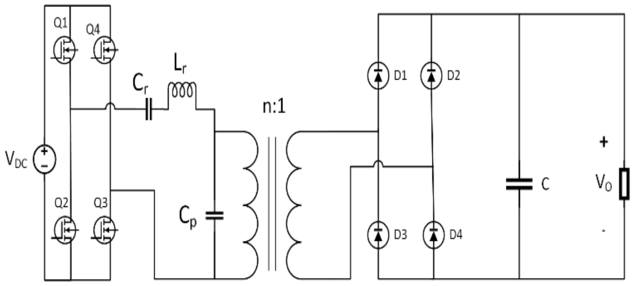

Fig.4. Circuit diagram of LCC resonant converter.

In LLC, resonant converter has two inductors and one capacitor as it is capable of adjusting the resultant voltage by connecting inductor in parallel [6] as shown in Fig.5.

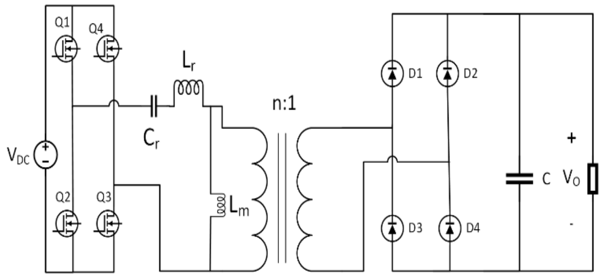

Fig.5. Circuit diagram of LLC resonant converter.

IV. MODULATION / CONTROL TECHNIQUES

The resonant converter efficiency is decided by passive components and power switches made of semiconductors. The modulation techniques used have important implications on efficiency of these conversion devices. Resonant converter modulation approaches are mainly as follows

A. Variable frequency control (VF)
B. Phase shift modulation control(PSM)
C. Self-sustained oscillation (SSOC)
D. Optimal trajectory control(OTC)
E. Self-sustained phase shift modulation(SSPSM)

A. Variable frequency control (VF)

In this technique, the voltage control is achieved by interchanging the switching frequency fs more than resonant frequency fr. One of the bridge's leg switches in resonant converter would be operated at 50% duty cycle and a phase shift of 180° maintained at control signals of the other leg of the suspension bridge. This control has a fixed on and off time which is variable in nature.

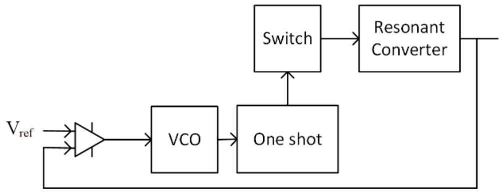

Fig.6. Resonant converter block diagram with VF.

Fig.6. shows the block diagram of variable regulation of frequency.

The output voltage and reference voltage is compared, error voltage obtained would be amplified and its output is applied to drive the VCO [7]. The converter requires that the VCO output trigger one shot with a defined pulse duration. The voltage mode control mechanism has been successfully implemented adopted here, as a result, it has a weak input transient response.

B. Phase shift modulation control (PSM)

PSM topology [7] is applicable to full bridge converters. Switches are located on each bridge, the phase angle of these two switches control signals are (180°-ϴ), while maintaining the duty ratio of the two voltage switches constant at 50%. Due to this, the inverter's output voltage is holded for a set period of time, and the duty ratio indicates the amount of time that power is pulled from the sources d = (1- ϴ/180). As a result, the control technique is successful by varying the duty cycle(d), with fs set higher than fr and zero current switching (ZCS) will be used on one bridge leg, while zero voltage switching will be used on the other (ZVS). The problem of this topology is that the inverters' current sharing is unequal, results in heating excessive. Other issue is that ZVS would be for one half of the system because one leg would loose ZVS. PSM resonant converter block diagram as seen in Fig 7. To modify inverter output voltage as per load, one leg's triggering is adjusted by an angle ϴ relative to the other leg.

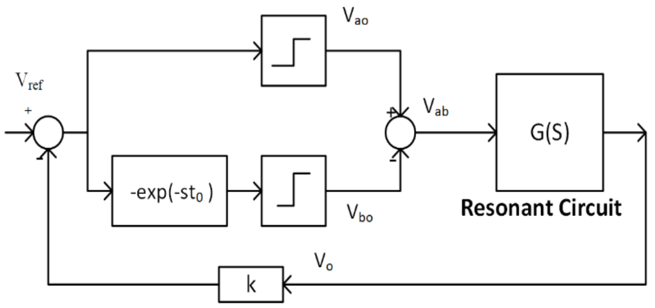

Fig.7. PSM resonant converter block diagram.

C. Self-sustained oscillation Control (SSOC)

Purpose of SSOC is to supervise the switching frequency providing voltage regulation and to achieve zero voltage switching, it has an inner loop and output voltage is controlled by the outer loop as per the reference value.

Inner loop adjusts the phase shift between the resonant current and inverter output voltage, which ensures that resonant current lags behind inverter output voltage to maintain ZVS as shown in Fig 8: Resonant converter block schematic in SSOC Mode. Resonant converters with self-sustaining oscillation [7] can also be characterized as a resonant converter operation in which externally switching frequency is uncontrolled, as in traditional variable frequency (VF) control, but instead permitted to vary with a frequency that depends on both the converter parameters and the phase shift required for ZVS.

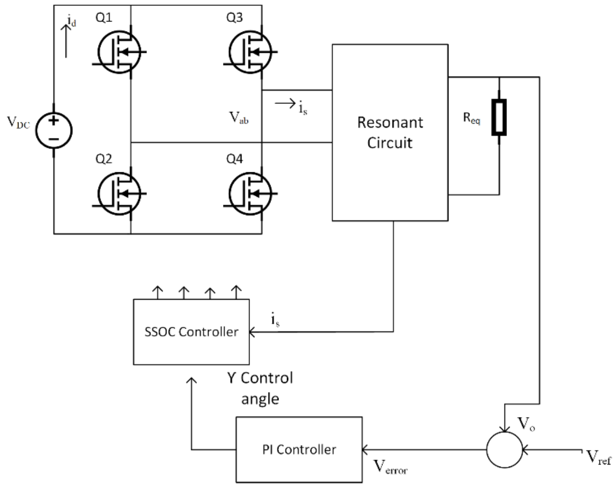

Fig.8. SSOC resonant converter block diagram.

D. Optimal trajectory control(OTC)

Optimal design technique is also termed as linear quadratic regulator (LQR) [7]. It is an example of a state-plane trajectory, the controller acts in accordance with the controller's trajectory with a definite path that holds resonant tank energy within fixed bounds. To begin, derive the circuit's state space model at one operational point. The next step is to determine the LQR for that particular operation. This control method has a quick transient response SSPSM follows next, followed by SSOC, then PSM, and finally by VF controller [7]. Fig.9. depicts a resonant block diagram in optimal control.

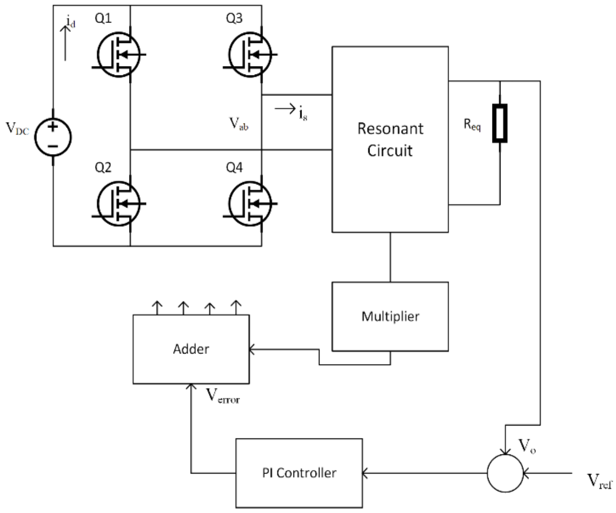

Fig.9. Block diagram of resonant converter in optimal control.

E. Self-sustained phase shift modulation (SSPSM)

This technique is obtained by the combination of SSOC and PSM to improvise the performance of variable frequency control technique [7]. The fundamental purpose of this method is to maintain simultaneous control of the switching frequency and width of PWM pulses, ensuring that the output voltage is maintained constant and the converter's ZVS operation is maintained. This is accomplished with the assistance of the inner loop and outer loop. These loops have the same characteristics as that of loops mentioned in SSOC. The block diagram of a resonant converter is shown in Fig 10.

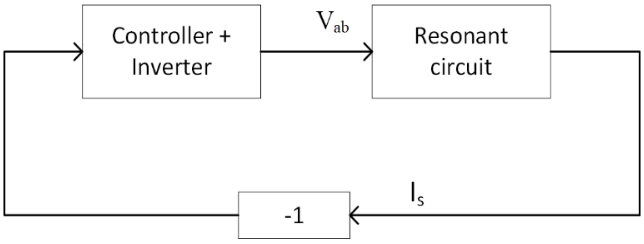

Fig.10. SSPSM resonant converter block diagram.

V.MODELLING TECHNIQUES

A. Fundamental Mode Approximation (FMA)

This method is the most commonly used frequency domain techniques [8] due to its speedy execution and simplicity for the design and analysis of resonant dc-dc converter. The current and voltage are considered as the basic component in FMA approach. The analysis of nonlinear systems can be conducted using this method, which provides the linear equivalent circuit. To fix a problem, typical AC circuit analysis is used, the system and transfer function are obtained to derive the converter's behavior and frequency response.

When the approach is used, it has concerns with accuracy, resonant tank current/voltages are away from harmonics and perfect sine waves are taken into account. To be able to improvise on the accuracy, Rectifier Transformed Fundamental Mode Approximation is proposed [9].

B. State Variable

This method is employed for time domain analysis of resonant dc-dc converter [10]. Traditionally, in converter circuits, the state variables in converter circuits are inductor current and capacitor voltage, these are the linear combinations of state variables and inputs of the system. The differential equations have been solved, as well as the transient and steady state properties are determined. Averaging state space [11]-[13] is a typical practice to acquire state variable average values. Waveform relaxation is another option [11] for nonlinear system analysis in the time domain [14].

C. Cyclic averaging

Cyclic averaging [15] is an accurate alternative method for state variable [16], this approach is also used for time domain analysis of resonant dc-dc converter [17]. Piecewise analysis can be carried out, the cycle is classified into m operational modes, m is the number of possible permutations of switches, m linear state variable equations are generated from a non-linear model [18] and state variable equations are obtained for each different modes from i=1,2,…m. The circuit works in each mode for a specific amount of time, which is determined by analysing the circuit's input voltage behavior across a cycle. This method helps in calculating averaged state vector or variables over a cycle, augmented vector technique employed for its simplification and this method helps in evaluating the harmonic analysis using fourier transform.

One of this method's disadvantages is to have the full-fledged knowledge of circuit behavior during the cycle for determining the operation modes and to calculate duty cycles.

Table 1. Different Resonant Converter Structures

RESONANT CONVERTER TYPE	FEATURES
Half bridge	• Power efficiency of 97.7% [19] • Solar cell power supply system compatible [19] • Suitable for High input voltage & Low input current
Full bridge	• Low input voltage and large input current are suitable. • Compatible with fuel cell power supply systems [19] • Power efficiency of 97.4% [19]
Push pull	• Low voltage to high voltage unregulated power conversion • Suitable for low voltage solar cell applications • Power efficiency of 93.5%
Series	• Reduced switching losses • Improve efficiency • High frequency operation reduces the size of magnetic components.
Parallel	• Suitable for high output current application • At no load, output regulation is not a concern.
Series-Parallel	• Simple control and less circuit components • Active device voltage stress can be decreased. • High switching frequency operation can be adopted

VI. CONCLUSION

A comprehensive review of topology, modeling and control technique has been accomplished to investigate on their various topologies and techniques to researchers, design engineers and application engineers. The topologies of resonant converters, the control techniques and modeling methods are elaborated briefly to furnish the simple selection of topology, modeling and control technique for wider applications. Every researcher looks for a high efficiency, low electromagnetic interference (EMI), low voltage stress, high energy density and high operation frequency. Therefore, depending on these parameters one should choose the right type of converter for the study.

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