Applied Electromagnetism in Trans-Z-Source Inverters

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Abstract

Traditional power converters possess numerous of limitations in power conversion such as low reliability or low flexibility in power transfer. In this paper, transformer-based Z-source (trans-ZSI) circuits are explored. Considerations for Z-source capacitors and inductors connections relating to the real model of the devices (e.g. ESR, Q, breakdown voltage, etc.) and how those parameters affect the DC/AC operation of the inverter are dicussed. Moreover, transformers and coupled inductors in the design are compared and analyzed in depth with three of Maxwell's equations. Furthermore, a deeper dive is done to study the Insulated-Gate Bipolar Transistors (IGBTs) with attached diodes and electromagnetic radiation (EMR) during the switching operations. Lastly, future work is considered to improve the capability of this technology.

Index Terms

Trans-Z-source Inverters, Inductors, Capacitors, IGBTs, power conversions, transformers, Maxwell's equations, power transistors, coupled inductors, electromagnetic radiation, EMI noise.

I. Introduction

In the power electronics world, achieving more power conversion capabilities at a lower cost is an ongoing task that researchers from all over world has been pursuing for decades. To convert from DC to AC, inverters are commonly used on applications such as motor drives or microgrids, and their circuitry varies one case to another with different number of elements being used to obtain desirable range of power outputs. One particular configuration that Peng [1] investigated was the impedance-source (Z-source) Inverters (ZSI). It is a unique set up, involving two inductors and two capacitors that are placed in between the DC source and the AC load, and which such configuration allows boost-buck capabilitily, minimizes component count and cost, and produces higher efficiency than traditional inverters. The research demonstrated that the Z-source topology are promising to act like a base for building better network use in different application of power conversion.

Qian et al. soon followed with a design called the Transformer-based Z-source (trans-ZSI) inverter [2]. The research proposed four different impedance networks involving a transformer and one capacitor. Not only can these four different circuits still retain the main functionality of the original Z-source network, but they also demonstrated an increase in voltage gain, a reduction in voltage stress, and a flexibility in motoring operating range for the three phase AC load. In this paper, two of the four trans-ZSI, the voltage-fed type and the current-fed type, will be explored in great details, specifically, Section II-A will show multiple considerations on how the passive elements in the circuits are chosen based on the real circuit models of those devices. In Section III, the transformer and coupled inductor are distinguished and show how Maxwell's equations applied to provide the power transfer. Located near the AC load, the IGBTs are discussed in Section IV along with the flyback diodes necessary for preventing voltage and current spikes during switching and how EMR can be negligible. Finally, in Section V, possible ideas on how to improve the inverter are discussed.

II. Circuit operations and elements considerations

A. Voltage-fed inverter

Fig.1 showed the configuration for the voltage-fed trans-ZSI where the circuit was built up from previous network of the Z-source inverter in Fig. 2 and traditional voltage-source converter in Fig. 3 1.

Because the trans-ZSI has similarities to the referenced circuits, it is necessary to talk about them separately. In traditional circuit, there is a DC link capacitor connected between the DC source and the AC load. The capacitor is necessary in any voltage-source power conversion because it ensures a smooth and stable output voltage. Also, it can prevent the transients from the load side to bounce back to the source due to its instrinsic capabability to store and release energy during switching cycles 1.

$$i_c = C\frac{dv_C}{dt} \tag{1}$$

The value of this DC link, or high-frequency bypass, capacitor is usually determined by different parameters [3], and for this application, the most important consideration is low equivalent series resistance (ESR), which represent the heat loss, or power loss, experienced by the capacitor due to the fact that the polarization $\boldsymbol{P}$ process lags the electric field $\boldsymbol{E}$ presented. With low ESR, the quality factor, Q, will be high, and the Dissipation Factor (D.F.) will be low. Two unimportant parameters worth mentioning are the dielectric absorption (D.A.) and equivalent series inductance (ESL). Even though there are a lot of switching on the load side, those are usually in the range of kHz and that will not create polarization, hence D.A. does not matter and ESL, typically in the range of nano Henries, can also be ignored. Therefore, a feasible material that meet those criteria for the inverter is Aluminum Electrolytes (Al. El.). Similarly to the traditional circuit, the voltage-fed trans-ZSI one still possess a DC link capacitor, C_1. When doing experiment, Qian et al. picked a $400\mu F$ capacitor in the circuit [2], and that is in the capacitance range of the Al. El. material mentioned.

However, due to its simplicity, the traditional inverter can only achieve one functionality at a time, either buck-boost, and it is prone to EMI noise from the switching, which will be discussed further in section IV, reducing the reliability of the inverter overall. Therefore, the Z-source inverter, involving an impedance network (Z-source) of two inductors and two capacitors placed in a unique way, replaced the single DC capacitor, or DC inductor in section II-B, can achieve buck and boost functionality through a single stage power conversion with higher efficiency and greater immunity to EMI noise. Thanks to the charging and discharging of the inductors and capacitors during the inverter swithing cycles, the load electronics can be better protected from EMI noise and the AC output voltage values varies greatly [1]. With less components, the voltage-fed trans-ZSI one transformer and one capacitor can replace the Z-source network to achieve the same benefits while providing a higher boost gain which is the ability to step-up the output voltage beyond the input voltage, allowing a wider range of application (e.g. solar microinverter, electric vehicle systems, etc.). Details about the transformer in the circuit is mentioned in section III.

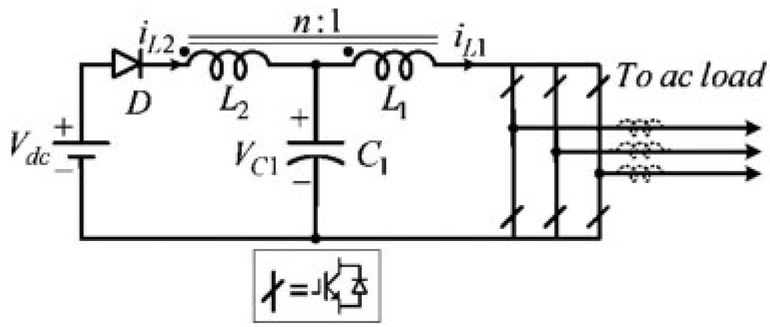

Figure 1. Votage-fed trans-ZSI. [2]

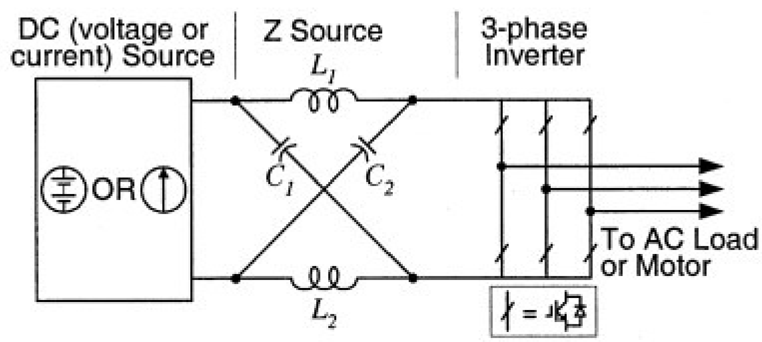

Figure 2. Z-source inverter.[1]

B. Current-fed inverter

Similarly, the current-fed counter part follows the same rules but with a DC link inductor, obsered in Fig. 5 and Fig. 4, instead of a capacitor to produce the effect of a smooth signal to the load and ensure no transient current from the load bouce back because current can not change instantaneously in an inductor (2). The choice of inductors for power converters applications are a bit different than the capacitors because less parameters need to be concerned. Due to low switching frequency (kHz region), apart from low DC resistance due to wires and eddy currents, R_{DC}, the main consideration would be a low Q value because that would lower AC resistance, R_{AC} (the ESR equivalent for inductors), where R_{AC} is dependent upon magnetization lags magnetic fields applied and proportional to a small B-H loop area, outputing less heat loss and more power transfer. In the

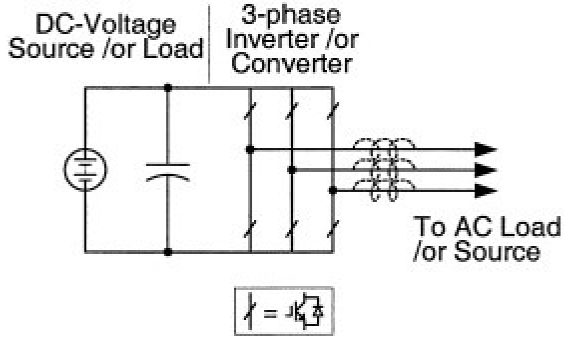

Figure 3. Traditional voltage-source converter.[1]

experiment Qian et al. conducted for the current-fed trans-ZSI circuit in Fig. 4, the DC link inductor, L_{DC}, is chosen to be 1 mH with a switching frequency of 10 kHz, which is a fairly large inductance value because more energy storage is needed for power supply application with relatively low frequency. Thus, a good structure of the inductor would be wire wound around a ferrite core or multilayered power inductors.

$$v_L = L\frac{di_L}{dt} \tag{2}$$

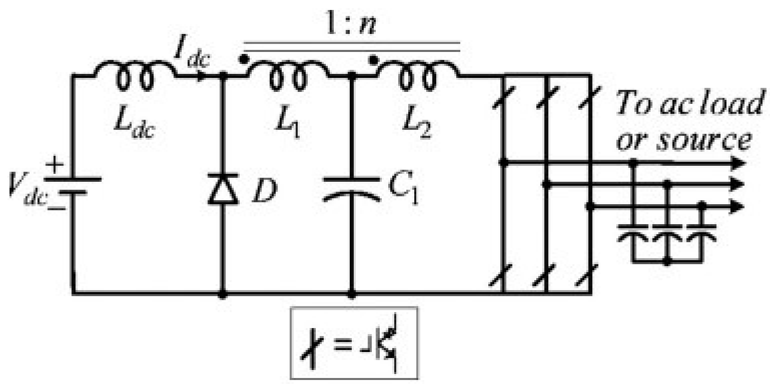

Figure 4. Current-fed trans-ZSI.[2]

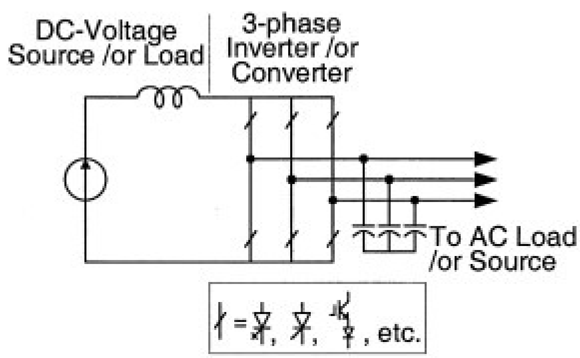

Figure 5. Traditional current-source converter.[1]

III. Transformer and Coupled Inductors

It can be seen in Fig. 1 and Fig. 4 that the turn ratios, n, of the transformer's winding of the voltage-fed and current-fed trans-ZSI are opposite. However, the transformer is presented in both to allow different advantages, determined by the windings ratio$\frac{n}{1}$ or $\frac{1}{n}$. In the voltage-fed circuit, if the turn ratio is greater than one, the inverter can see a higher boost gain and less component count. The same idea applied to the current-fed circuit, but due to the turn ratio of less than one, the transformer is stepping down the voltage and raising the current, which can allow an extended motoring operation range compared to the original Z-source [2].

A. Maxwell equations

To achieve the currents to the AC load from the DC source magnetizing currents, two fundamental laws of electromagnetism are required. The transformer are essestially inductors wrapped around a ferromagnetic iron core for higher magnetic field strength and inductance, so when there is a current going around a wrapped wire, Ampere's Law in (3).

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{3}$$

Due to the structure of the first solenoid, or the primary coil, the magnetic field created by the source will expand outwards and meet another solenoid, or secondary coil, with a different winding count. At that moment, Faraday's Law in (4) shows that a changing magnetic field density $\boldsymbol{B}$ can induce an electric field $\boldsymbol{E}$intensity, hence creating a voltage and current going through the other side.

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{4}$$

Also, it is shown in [4] that Gauss's Law for magnetic fields (5) also applies stating that there are no monopoles magnets and how $\boldsymbol{B}$ and $\boldsymbol{H}$are related to each other by the permeability of free space μ_0, equal to $4\pi \times 10^{-7} H/m$, and the relative permeability of ferromagnetic material μ_r , equal to approximately a value in the order of 10^3or 10^4:

$$\nabla \cdot \boldsymbol{B} = 0 \tag{5}$$

$$\boldsymbol{B} = \mu \boldsymbol{H} = \mu_r \mu_0 \boldsymbol{H} \tag{6}$$

One thing to mention is that the transformer is supplied by a AC source, so there can be changes in the voltage $\frac{dv}{dt}$, inducing current $\frac{di}{dt}$ and voltage on the secondary side.

B. Transformer and Coupled Inductor

In the trans-ZSI circuit, the transformer is not really a transformer. It is observed to perform like coupled inductor (CL) most of the time [2], and the difference between a transformer and CL can be seen through the magnetic model and electrical model of the two devices in Fig. 6 and Fig. 7, respectively [4]. From the models, it is clear that the key difference in structure is the air gap. Although it looks like a small gap, the entire circuit can operate differently when these two devices are presented in a system. Specifically, the magnetizing current I_m, closely related to the magnetizing inductance L_m based on the electrical model, in the trans-ZSI circuit will be small if the transformer is instead put in rather than the CL, potentially causing a failure of operation in the circuit. Therefore, it is necessary to know the difference between the two for the trans-ZSI.

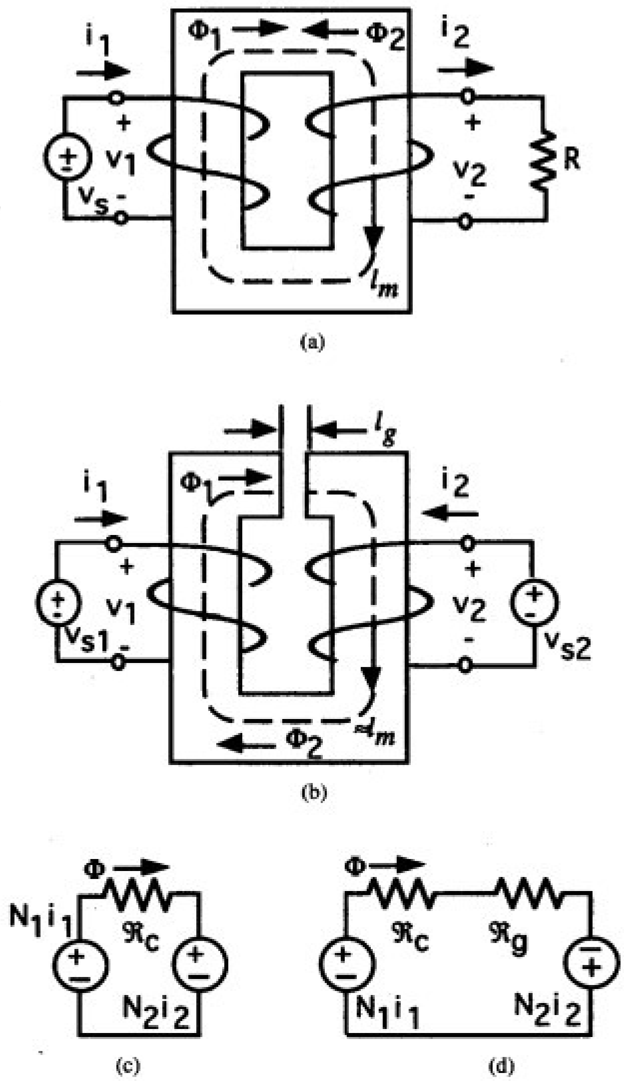

Figure 6. Structure of (a) transformer and (b) coupled inductor, and magnetic model of (c) transformer and (d) coupled inductor [4]

IV. IGBTs, diodes, and EMR

A. IGBTs and Diodes

1) Why IGBTs?: In both the voltage-fed in Fig. 1 and current-fed in Fig. 4 circuits, six IGBTs are used to perform the fast switching for AC voltage output, which drives the 3-phase motor. In theory, other switches namely BJTs, MOSFETs, or thyristors, can be used for the circuit, but why use IGBTs? To determine what type of switch to choose for what purpose, there are a lot of aspects to consider like cost, switching frequency, voltage and current considerations for applications. For the trans-ZSI, since switching speed falls around kHz region, it is best to choose IGBTs because that fits in its operating region as well as having the ability to handle high voltage and high current, allowing for optimized power transfer [5].

2) Attached Diodes : In Fig. 1 and Fig. 4, it is noticable that the IGBTs from the voltage-fed configuration and its current counterpart differ from the diode placement, where the diode is attached anti-parallel to the switch in the voltage-fed circuit but in series with the switch in the other one. The combination of an IGBT with a diode is called a reverse blocking IGBT,

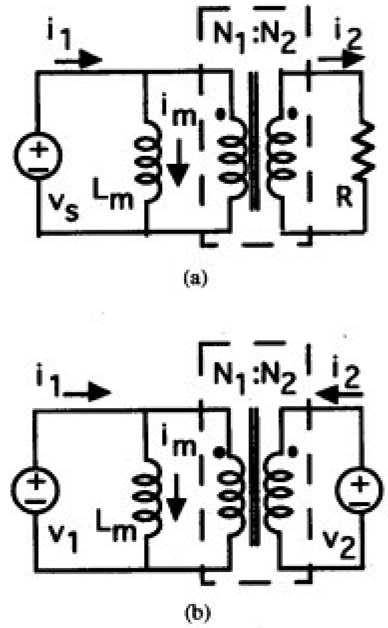

Figure 7. Electrical models: (a) transformer (b) coupled inductor [4]

or RB-IGBT, and they prevent voltage spikes in the voltage-fed circuit and current spikes in current-fed circuit.

When switching happens, because the inductor in the RL load will resist to changes and $\frac{di_L}{dt}$ will theoretically go to infinity, voltage spikes will happen. Therefore, these freewheeling, or flyback diode, allow another path for current to go through, preventing those spikes from happening. Also, the diode is usually placed in a reverse-biased direction to the power supply side to prevent current from there to flow through when voltage is applied. The same principle also apply for the current source circuit where it can prevent the current spike from the bypass capacitors from the load.

B. Electromagnetic radiation

When a switch flips 10,000 times per seconds, that can create a lot of noise, not sound but electromagnetic interference (EMI), or noise, in the form of waves that could radiate to the electronics in the load and interfer with the circuit operations. Biswas et al. came up with a parasitic model of the IGBT with parasitic inductors (L_C, L_E), parasitic capacitors (C_{P_1}, C_{P_2}), and a leakage resistor (R_L) in Fig. 8. It is found that noticable noise can be identified around 2.5 MHz during turn-on and 230 MHz during turn-off, and that the turn-off Electromangetic Radiation spectrum has greater noise level and high peak frequency, which can be a good indicator for the health of the IGBT and inverter. However, the trans-ZSI network typically operates at a lower frequency, so EMI can be ignored for this application.

V. Future research and innovations

From all of its benefits, trans-ZSI is proven to be a good base for future research. This promising configuration can achieve higher level of efficiency in so many ways. The materials used in CL can be researched in depth to find higher μ_r values for more magnetic field strength and less loss. Inductors and capacitors technology can be improve to provide better energy storage as well as power transfer capabilitity with a smaller Q and higher rated current for inductors, or higher Q and lower ESR

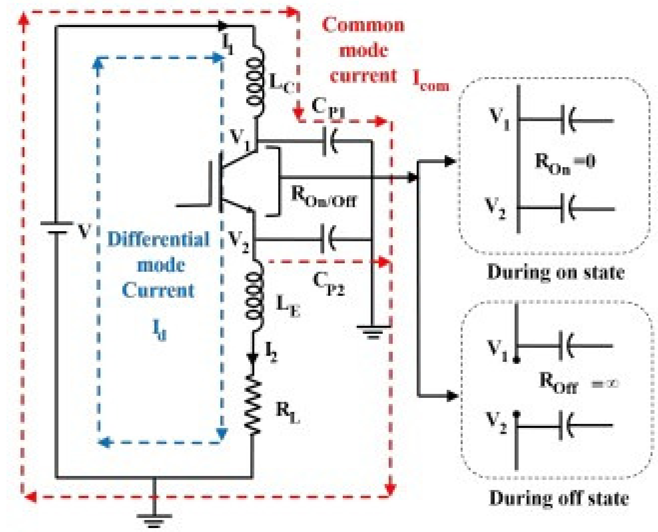

Figure 8. IGBT parasitic model [6]

in capacitors. Moreover, with a goal of reducing component counts and cost while maintaining the same efficiency in power transfer, new circuit design topologies involving different novel elements or variable passive elements can be explored, for example, Zener Diodes, used for voltage regulation, can replace the normal power diodes to possibly act as a voltage-controlling or protective element. On top of that, for high-voltage applications, such as electric grid transmission or distributions lines, relays can be explored on this type of circuits. Lastly, higher switching frequency can produce better waveform of the AC output voltage, so high frequency research for the trans-ZSI can produce great benefits.

VI. Conclusion

A study on two type of trans-ZSI circuits, voltage-fed and current fed, is shown, and where electromagnetic theory applies. The circuit operations are observed along with different aspects when picking the passive elements. Three Maxwell's equations are explored in relation to the transformer and the coupled inductor in the circuit and how they can work with other elements to deliver the buck-boost functionality. IGBTs and attached diodes are analyzed in details while EMI noise generated from the switching is conclude to be negligible. Lastly, many possibilities for this technology to go forward is discussed.

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