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Comparative Analysis of Magnetically Coupled Z-Source Inverters

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Abstract-- **Z-source inverters are a new class of inverters proposed with output voltage or current buck–boost ability. And also its having limitations as mainly two.one is not flexible to provide continuity to inductor current, and second was there is coupling effect between modulation index and duty ratio. Its effects property of inverter. To minimize these concerns, an motivating methodology is to use magnetically coupled transformers or inductors to raise the gain and modulation ratio simultaneously, with reduced components .in this paper I proposed the magnetically coupled type inverters by developing with help of genetic methodology.**

By comparing all magnetically coupled topologies the gamma source inverter shows matured characteristics.i.e the proposed topology use lesser turns ratio to produce same level of output. Other than gamma source inverter other topologies need infinite turn's ratio to produce infinite gains. But proposed topology need 1:1 transformer enough to produce infinite gains.

***Index Terms*—z-source inverter, Trapped inductor ZSI, Cascaded ZSI,Trans z-source inverter,Γ-SI,flipped ΓSI**

I. INTRODUCTION

THE application of power converters has grown rapidly, particularly with the recent proliferation of renewable energy, distributed generation, and more electric vehicles[9]. This trend is expected to continue and would therefore demand more challenging converters to be developed.now a day's renewables plays vital role and that to PV Cells and Fuel Cells and MHD's in the case of thermal power stations to increase conversion efficiency. Solar cells and fuels still going to increase their generating capability. Output power of renewable not bat all constant because input available energy is unpredictable in nature.in order to meet grid requirements we need a powerful converter(shown in fig. to interface 1) renewables and grid system with boosting flexibilities. Prior to Z-source[2-6] the boost inverter, buckboost inverter,chuk[1] type topologies are very popular. Z_source[2-6] are inviting by F.Z.Feng at 2002,with voltage are current buck boost availability. And also those topologies have inherent short-circuits protection and also open-circuit protection which was drawbacks of VSI,CSI ,respectively.

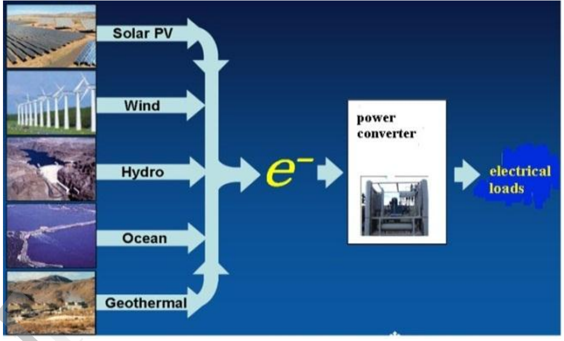


Figure1.alternatives for electrical energy generation

The development impedance-source inverters says mainly two ways

1. Primary revolution
2. Secondary revolution

The traditional Z-source inverter and its modifications.(quasi-ZSI, embedded ZSI, embedded dc bus ZSI)[11-12] & trapped inductor based models, hybrid models(cascaded types)[15] coming under primary revolution.

The magnetically coupled ZSI[19-21] makes secondary revolution. And this type of topologies shows matured characteristics compared to primary stage ZSI's.is Cleary mentioned in fig.2.

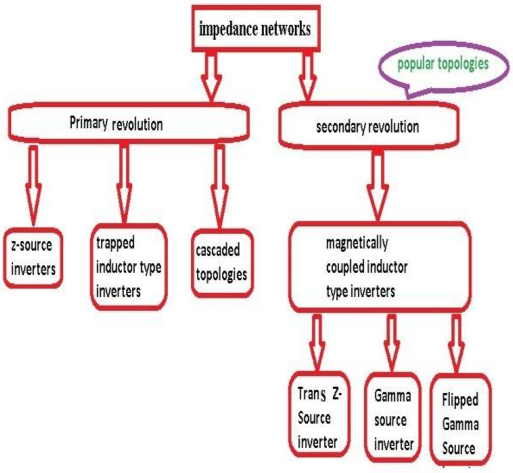


Figure2.impdence-source inverters

II. PRIMARY STAGE IMPEDANCE MODELS

TRADITIONAL

1. *Traditional Z-source inverters*

These types of topologies are primary models in impedance networks.by placing X-shaped LC components in between source and inverters

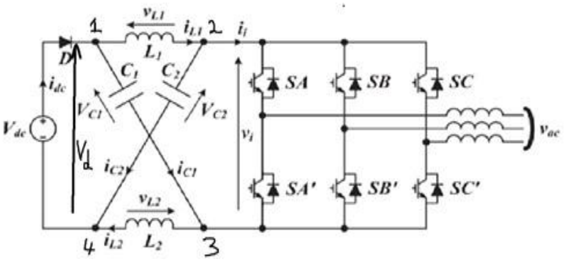


Figure3.Z-source inverters

Genetic derivation methodology

The equation analysis is clearly discussed below

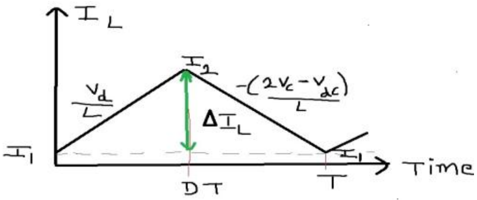


Figure4.inductor current in ZSI

Shoot through mode

$$\mathrm{Vd} - \mathrm{Vi} = \mathrm{L}\frac{diL}{dt}$$

$$\mathrm{iL(t)} = \frac{1}{L}\int_0^t (Vd - Vi)dt + iL(0)$$

$$\mathrm{iL(t)} = \frac{Vd-Vi}{L} * t$$

Peak at t=DT

$$\mathrm{iL(DT)peak} = \frac{Vd-Vi}{L} * DT + iL(0)$$

Peak-peak ripple current

$$\mathrm{iL} = \mathrm{iL(DT)} + iL(0)$$

$$\Delta\mathrm{iL} = \frac{Vd-Vi}{L} * DT$$

$$\boldsymbol{\Delta \mathrm{iL}} = \frac{\mathbf{2*Vc}}{\mathbf{L}} * \mathbf{DT} \rightarrow ❶$$

Active mode

$$\mathrm{Vd} - \mathrm{Vi} = \mathrm{L}\frac{diL}{dt}$$

$$\mathrm{iL(t)} = \frac{1}{L}\int_{DT}^t (Vd - Vi)dt + iL(DT)$$

$$\mathrm{iL(t)} = \frac{Vd-Vi}{L} * (t\text{-DT}) + \mathrm{iL(DT)}$$

Minimum at t=T

$$\mathrm{iL(DT)peak} = \frac{Vd-Vi}{L} * \mathrm{DT} + iL(\mathrm{DT})$$

Peak-peak ripple current

$$\mathrm{iL} = \mathrm{iL(DT)} + iL(\mathrm{T})$$

$$\Delta\mathrm{iL} = \frac{-(Vd-Vi)}{L} * (1 - D) * T$$

$$\boldsymbol{\Delta iL} = \frac{\mathbf{2*(Vc-Vdc)}}{\boldsymbol{L}} * (\mathbf{1} - \boldsymbol{D}) * \boldsymbol{T}\,) \rightarrow ❷$$

By volt-sec balance principle ❶=❷

$$\boldsymbol{Vc} = \frac{\mathbf{1-D}}{\mathbf{1-2D}} * \boldsymbol{Vdc} \qquad \textbf{Finally } \boldsymbol{Vi} = \frac{\mathbf{1}}{\mathbf{1-2D}} * \boldsymbol{Vdc}$$

RMS value of ac voltage

$$\mathrm{Vac} = \mathrm{M} * \frac{\mathrm{Vdc}}{2} \quad \text{(In case of normal inverter)}$$

$$\mathrm{Vac} = \mathrm{M} * \mathrm{B} * \frac{\mathrm{Vdc}}{2} \quad \text{(In case of Z- Source inverter)}$$

Major disadvantages of ZSI

1. Not flexible to provide continuity to inductor currents
    - ➢ It effects on inductor size and max frequency limit
2. Coupling effect between modulation index and shoot through duty ratio

   $\text{Boost factor}\uparrow B = \frac{Vi}{Vdc} = \frac{1}{1-2D\uparrow}$

   $\text{gain}\uparrow\text{G} = \frac{Vac}{Vdc} = \frac{\mathrm{M}\downarrow}{1-2D\uparrow} = \mathrm{M*B}$

   $\text{Where } \uparrow\text{D} = 1\text{-M}\downarrow = 1 - \frac{V_{r\downarrow}}{V_c}$

2. *Trapped inductor type ZSI*

The inductors going into modify such way that the high gain requirements. Here energy can transfer in both modes

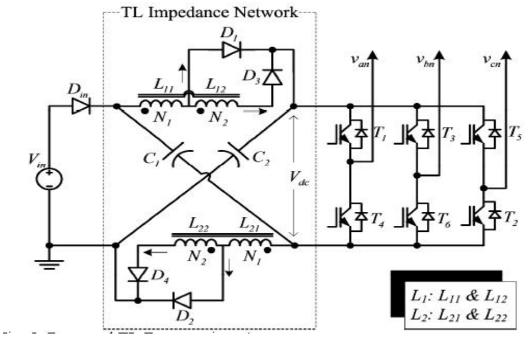


Figure5.trapped inductor Z-source inverters

It’s really show improvement to provide continuity to inductor currents so inductor size come down further by this topology. But the coupling effect still persists in network.

3. *Hybrid ZSI(cascaded ZSI)*

In this type of topologies we can increase boost factor and gain but still the drawbacks is following along this model.

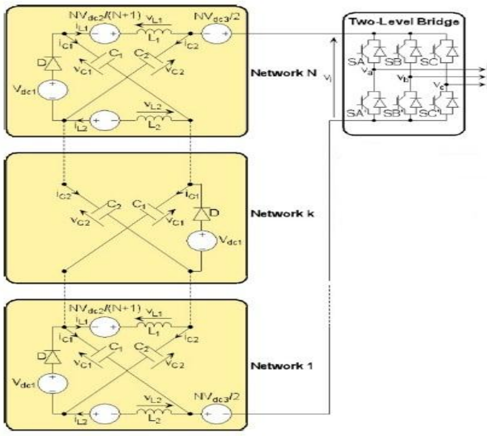


Figure6.trapped inductor Z-source inverters

III. SECONDARY STAGE IMPEDANCE MODELS

This model is also called as magnetically coupled models.by eliminating all drawbacks in primary models eliminated by these models. See given table and fig.7 for further details.in that table we can observe that there is alternative for gain increment is turns ratio in magnetically coupled converters. Its eliminates coupling effect because doesn’t vary the modulation inductor and so duty ratio

D(constant)= 1-M(constant)

TABLE I

	Boost converter	*Z-Source Inverter*	*Magnetically Coupled Z-Source Inverter*
Boost factor(B) ↑	$\frac{1}{1-d\uparrow}$	$\frac{1}{1-2d\uparrow}$	$\frac{1}{1-(\gamma\uparrow+1)*d}$
Input to output gain(G) ↑	No ac conversion	$\frac{0.5*M\downarrow}{1-2d\uparrow}$	$\frac{0.5*M}{1-(\gamma\uparrow+1)*d}$

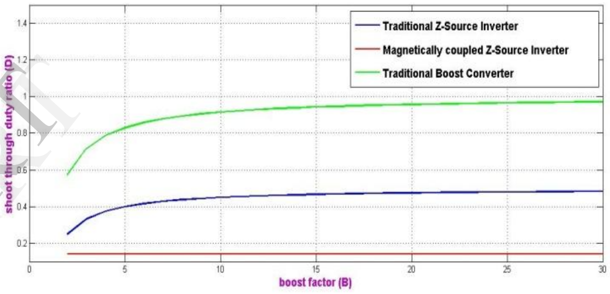


Figure7.duty ratio relationship among impedance source inverters

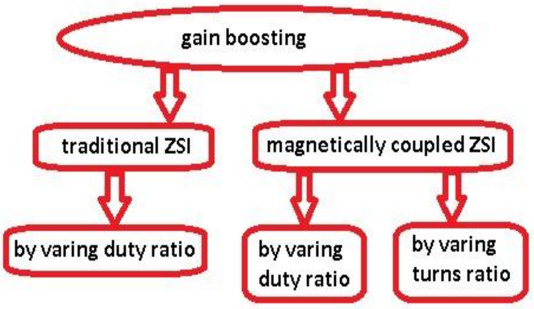
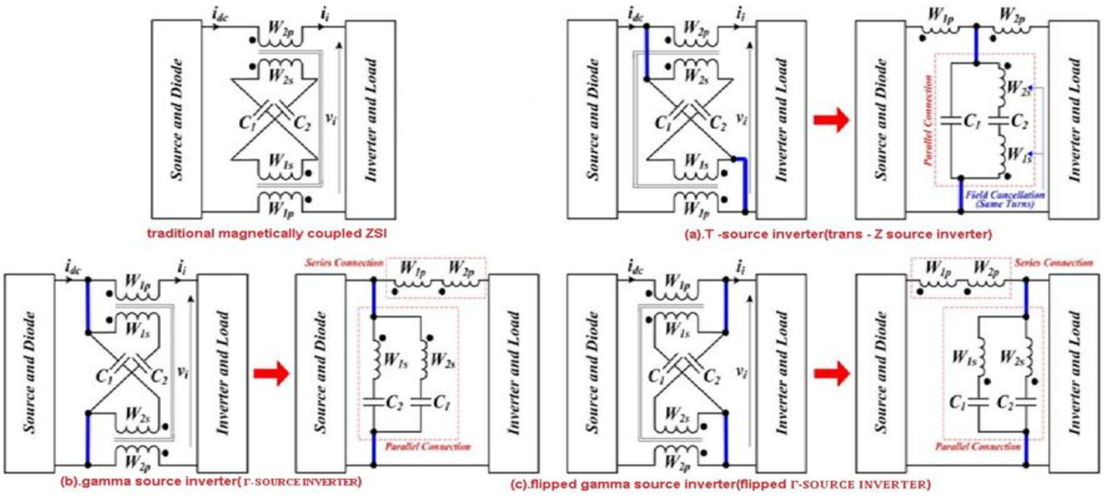


Figure8.alternatives to boost gains

Above figure clearly explains how the magnetically coupled ZSI are going to eliminates the coupling effect called D=1-M by making M as constant.

IV. CONCEPT OF MAGNETICALLY COUPLED Z-SOURCE INVERTERS



traditional magnetically coupled ZSI

(a).T -source inverter(trans - Z source inverter)

(b).gamma source inverter(Γ-SOURCE INVERTER)

(c).flipped gamma source inverter(flipped Γ-SOURCE INVERTER)

Fig 9.basic block diagram of developments of impedance networks

TABLE -II DERIVATIVE EXPLORATION OF MAGNETICALLY COUPLED ZSI

Feature	Traditional Z-source	Mutually coupled inductor type			comments
		Trans Z-Source (TZ)	Γ – Source (Γ)	Flipped Γ – Source (fΓ)	
Turns ratio relationship for gain equalization	Not applicable	$\gamma_{TZ} = \frac{1}{\gamma_\Gamma - 1} = \gamma_{f\Gamma} - 1 = \frac{W1}{W2}$ 5.1(a)			-when5.1 (a)=1,response of traditional and mutually coupled inverters are same
Turns ratio trend & range	Not applicable	Increasing $1 \le \gamma_{TZ}$	Decreasing $2 \ge \gamma_\Gamma > 1$	Increasing $2 \le \gamma_{f\Gamma}$	-$\gamma_{TZ}$and$\gamma_{f\Gamma}$ can becomes excessive at high gain -γ_Γ approaches 1 at high gain -$\gamma_{f\Gamma}$ demands the most turns
Range of modulation ratio M	0≤M_x≤1.15*(1-d_x)				-Upper limit d_x required can be made smaller than 0.5 by adjusting γ_x -upper limit of M_x can be high even at high gain
Range of shoot-through duty ratio	0≤d_t<0.5	$0 \le d_{TZ} < \frac{1}{\gamma_{TZ}+1}$	$0 \le d_\Gamma < \frac{1}{1+\frac{1}{\gamma_\Gamma - 1}}$	$0 \le d_{f\Gamma} < \frac{1}{\gamma_{f\Gamma}}$	
Capacitor voltage Vc	$\frac{(1-d_t)*Vdc}{1-2*d_t}$	$\frac{(1-d_{TZ})*Vdc}{1-(\gamma_{TZ}+1)*d_{TZ}}$	$\frac{(1-d_\Gamma)*Vdc}{1-\left(1+\frac{1}{\gamma_\Gamma-1}\right)*d_\Gamma}$	$\frac{(1-d_{f\Gamma})*Vdc}{1-\gamma_{f\Gamma}*d_{f\Gamma}}$	-same for all mutually coupled inverters if (a) satisfied
DC link Voltage Vi	$\frac{Vdc}{1-2*d_t}$	$\frac{Vdc}{1-(\gamma_{TZ}+1)*d_{TZ}}$	$\frac{Vdc}{1-\left(1+\frac{1}{\gamma_\Gamma-1}\right)*d_\Gamma}$	$\frac{Vdc}{1-\gamma_{f\Gamma}*d_{f\Gamma}}$	
Peak output voltage Vac	$\frac{0.5*M_t*Vdc}{1-2*d_t}$	$\frac{0.5*M_{TZ}*Vdc}{1-(\gamma_{TZ}+1)*d_{TZ}}$	$\frac{0.5*M_\Gamma*Vdc}{1-\left(1+\frac{1}{\gamma_\Gamma-1}\right)*d_\Gamma}$	$\frac{0.5*M_{f\Gamma}*Vdc}{1-\gamma_{f\Gamma}*d_{f\Gamma}}$	
Shoot -through current i_i	2*i_{dc}	$(\gamma_{TZ}+1)*i_{dc}$	$\frac{\gamma_\Gamma*i_{dc}}{\gamma_\Gamma-1}$	$\gamma_{f\Gamma}*i_{dc}$	-shoot-through currents generally high
Magnetizing current i_m at low voltage winding	2*i_{dc} (2*current i_L)	$(\gamma_{TZ}+1)*i_{dc}$	$\gamma_\Gamma*i_{dc}$	$\gamma_{f\Gamma}*i_{dc}$	-value of TZ& fΓ are the same if (a) satisfied -value for Γ is smaller

1. *Trans Z-Source Inverters*

By replacing traditional inductors by coupled transformer and simplified such a way that two form trans z-source network. Generally the name trans Z-source called T- source is mainly due to the shape of impedance circuit is clearly showed in fig.9 (a).

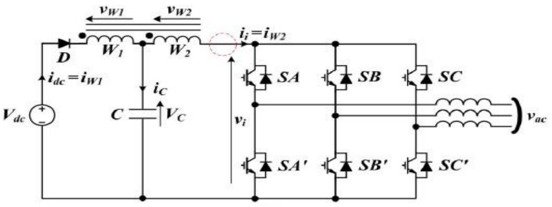


Fig10.circuit diagram of Trans Z-source inverter

Circuit analysis

a) ***shoot trough***: diode is OFF and two switches in same leg ON at the same time to form shoot trough

$$Vw1=\gamma TZ* Vw2 ; Vw2=Vc.$$

b) ***non shoot trough*****:** diode is ON and inverter acts they own work to form active state

$$Vw\,2 = Vdc - VC ; Vw\,1 = Vdc$$

Capacitor voltage: $Vc = \frac{(1-D\Gamma)*Vdc}{1-(1+\gamma T)D\Gamma}$

DC link voltage: $Vi = \frac{Vdc}{1-(1+\gamma T)D\Gamma}$

AC RMS voltage: $Vac = \frac{0.5*M*Vdc}{1-(1+\gamma T)D\Gamma}$

2. *gamma(Γ) source inverters*

By replacing inductors by coupled parameters and is shown clearly in the fig.9(b).it was the best and matured topology among all magnetically coupled models and that discussed later.

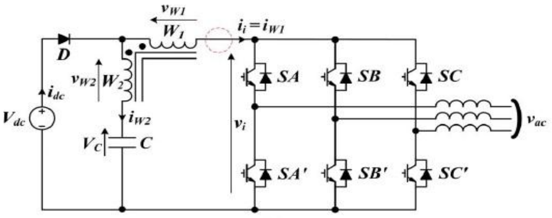


Fig11.circuit diagram of gamma-source inverter

Circuit analysis

a) ***shoot trough*****:** diode is OFF and two switches in same leg ON at the same time to form shoot trough

$$Vw1=Vw2+Vc ; Vw2=Vc/(\gamma TZ-1) .$$

c) ***non shoot trough*****:** diode is ON and inverter acts they own work to form active state

$$Vw\,2 = Vdc - VC ; Vw\,1 = \gamma\Gamma Z* Vw2$$

Capacitor voltage: $Vc = \frac{(1-D\Gamma)*Vdc}{1-(1+\frac{1}{\gamma\Gamma-1})D\Gamma}$

DC link voltage: $Vi = \frac{Vdc}{1-(1+\frac{1}{\gamma\Gamma-1})D\Gamma}$

AC RMS voltage: $Vac = \frac{0.5*M*Vdc}{1-(1+\frac{1}{\gamma\Gamma-1})D\Gamma}$

3. *Flipped Gamma(ꓶ) source inverter*

By replacing inductors by coupled parameters and is showed clearly in the fig 9(c).this topology impedance source is flipped impedance of gamma source.

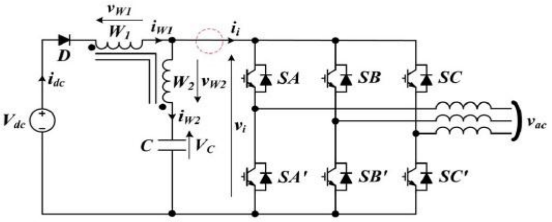


Fig11.circuit diagram of flipped gamma-source inverter

Circuit analysis

a) ***shoot trough***: diode is OFF and two switches in same leg ON at the same time to form shoot trough

$$Vw1=\gamma TZ* Vw2 ; Vw2=Vc.$$

b) ***non shoot trough*****:** diode is ON and inverter acts they own work to form active state

$$Vw\,2 = Vdc - VC-(\gamma ꓶ-1)Vw1 ; Vw\,1 = Vdc$$

Capacitor voltage: $Vc = \frac{(1-D\Gamma)*Vdc}{1-(\gamma f\Gamma)D\Gamma}$

V. TOPOLOGICAL COMPARISON OF MAGNETICALLY COUPLED INVERTERS

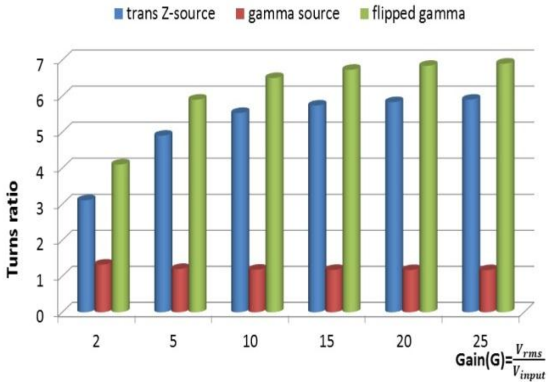
A. GAIN EQUILISATION:

Input to output gain $\frac{Vi}{Vdc} = \frac{0.5*M}{1-2*D0} = \frac{0.5*M}{1-(\gamma TZ+1)*DTZ} = \frac{0.5*M}{1-\left(1+\frac{1}{\gamma_\Gamma-1}\right)D_\Gamma} = \frac{0.5*M}{1-\gamma_{f\Gamma}*D_\Gamma}$

TABLE- III Turns ratio requirement to reach gain demands

gain	Z-source	Trans Z-source		Γ-source		Flipped Γ-source	
G	D0	DTZ	1 ≤ γTZ	DΓ	2≥ γΓ > 1	D fΓ	2 ≤ γ fΓ
2	0.3937	0.14	3.107	0.14	1.3218	0.14	4.107
5	0.4575	0.14	4.92855	0.14	1.2029	0.14	5.928
10	0.47875	0.14	5.535	0.14	1.1806	0.14	6.535
20	0.4893	0.14	5.8392	0.14	1.171	0.14	6.839
50	0.49575	0.14	6.0214	0.14	1.1661	0.14	7.0214

Fig12.gain variations in magnetically coupled topologies



The above table and figure.12 says that compare to other topologies the gamma source inverter needs lesser turns ratio transformer for producing higher gains. And not only single concern, the Trans Z-source and Flipped Gamma source needs almost turns ratio= infinity to produce infinity .i. e$\gamma_{TZ}, \gamma_{f\Gamma \to \infty}$ at high gains. But the gamma source inverter needs turns ratio $\gamma_{\Gamma \to 1}$.so the gamma source inverters going to produce higher gains at 1:1 transformer as placed there.it makes the size and weight low.

B. COUPLED TRANSFORMER PERAMETERS

Whenever we are using coupled parameters we must analyze how the magnetizing inductance and flux going to varies and what was the flux strength, those parameters must help to design transformers according to requirements.

$$\{L_m^1\}_{TZ} = \{\frac{\gamma_{TZ}}{\gamma_{TZ}+1}\}^2 * \{L_m^1\}_\Gamma$$
$$= \{\frac{\gamma_{TZ}}{\gamma_{TZ}+1}\}^2 * \{L_m^1\}_{f\Gamma}$$

If we substitute the turns here means we got below equation.it says the gamma source and flipped gamma source must need higher magnetizing inductance to store energy

$$\{L_m^1\}_{TZ} = 0.489 * \{L_m^1\}_\Gamma = 0.489 * \{L_m^1\}_{f\Gamma}$$

By comparing all topologies we can says that gamma source inverter shows matured characteristics for voltage as a source.

TABLE –IV

DESIGN ASPECTS OF SIMULATION OF VOLTAGE TYPE GAMMA SOURCE INVERTER

Components	**Values**
Source	**V_{dc} = 100 V**
Magnetically coupled impedance parameters	**Winding turns(w1)=66** **Winding turns(w2)=46** **Turns ratio(γ_Γ)=1.43** **Coefficient of coupling(k)=0.999** **Mutual inductance(L_m)=0.4145mH** **Total transformer resistance=0.091 Ω** **Z-source capacitance C=220µF**
Inverter	**f_c =10 KHz** **f_r =50 Hz** **M_Γ = 0.85*1.15(3rd harmonic)** **d_Γ =$d_{f\Gamma}$ =0.14 (boost)** **d_Γ =$d_{f\Gamma}$ =0 (buck)**
Filter	**L=6.3mH/phase**
Load	**Resistive: R=25Ω/phase** **Motor: 4KW(5HP),400V,1450RPM**

VI. RESULTS AND DISCUSSIONS

The gamma source inverters produces output voltages Vrms,Vc and fundamental components as given below

1.Capacitor voltage

$$Vc = \frac{(1-Dr)*Vdc}{1-(1+\frac{1}{\gamma r-1})Dr} = \frac{(1-0.14)*100}{1-\left(1+\frac{1}{1.43-1}\right)*0.14} = 160.922 \text{ volts}$$

2.D.C Link voltage

$$Vi = \frac{Vdc}{1-(1+\frac{1}{\gamma r-1})Dr} = \frac{100}{1-\left(1+\frac{1}{1.43-1}\right)*0.14} = 187.11 \text{ volts}$$

3.A.C RMS voltage

$$Vac = \frac{0.5*M*Vdc}{1-(1+\frac{1}{\gamma r-1})Dr} = \frac{0.5*0.85*100}{1-\left(1+\frac{1}{1.43-1}\right)*0.14} = 79.52 \text{ volts}$$

The same output voltage can produce by using Trans Z-source[18-19] and Flipped Gamma source also but the only change is orientation of connection and turns ratio requirement. That can be explaining clearly by using given equation and table.

$$\boldsymbol{\gamma TZ = \frac{1}{\gamma r - 1} = \gamma fr - 1}$$

Where γTZ= turns ratio in Trans Z-source

γΓ=turns ratio in gamma source

γfΓ =turns ratio in flipped gamma source

TABLE –V TURNS RATIO REQUIREMENT

Topology type	**Turns ratio symbol**	**Turns ratio=W1/W2**
Trans Z – source(T - Source)	$\boldsymbol{\gamma TZ}$	2.3255 (medium)
Γ-source inverters	γr	1.43 (low)
Flipped Γ-source inverters	γfr	3.3255 (high)

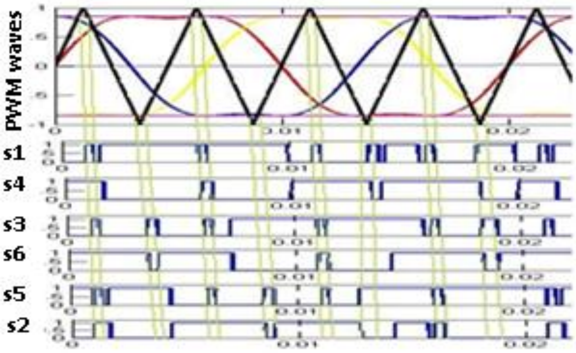


Fig8.maximum constant boost PWM techniques

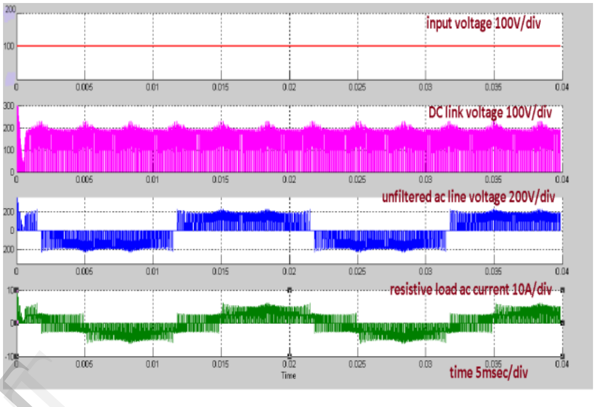


Fig.(9a) Simulink input, dc-link and output waveforms of Γ-Z-source inverter when in voltage-boost mode in R-LOAD

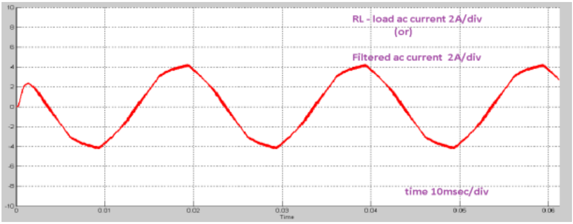


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Fig (9b).output current waveforms of Γ-Z-source inverter when in voltage-boost mode in RL-LOAD

Fig.(9c). Simulink dc-link and winding waveforms of Γ-Z-source inverter when in voltage-boost mode.

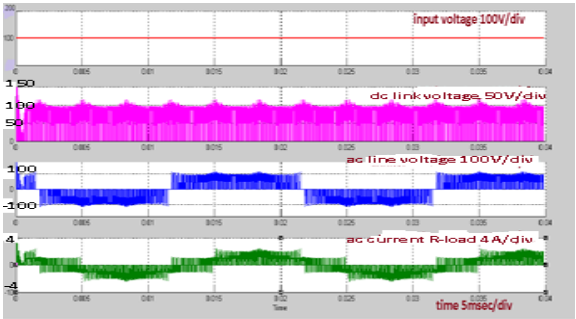

Fig. (10). Simulink input, dc-link and output waveforms of Γ-Z-source inverter when in voltage-buck mode.

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