

# **TOPOLOGICAL VARIATIONS OF THE INVERSE DUAL CONVERTER FOR HIGH POWER DC-DC APPLICATIONS**

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**Abstract-** New dc to dc converter topologies are presented which are suitable for high density high power supplies. Topological variations of the basic inverse dual converter (IDC) circuit such as the transformer coupled, the multiphase and the multipulse derivation of the single phase IDC have been analysed and some simulation results have been presented. It has been shown in a recent publication [1] that the single phase IDC offers a buck-boost operation over wide range without transformer, bidirectional power flow, and complementary commutation of the switches.

The topologies examined in this paper have additional features such as lower device and component stresses, and smaller filter requirements, resulting in smaller size and weight. Some performance and possible applications are also examined.

Finally the IDCs for serial and parallel power distribution, and ac tapping of the IDC are discussed.

## **Introduction**

High power dc to dc conversion has been receiving an increasing interest in the past years as the result of increased demand for high power converters in aerospace, defence and terrestrial applications. At the present time a wide selection of switch mode topologies, based on pulse width modulated (PWM) or resonant power processing, are available for implementation at lower power levels, up to several hundred Watts. However the medium and especially high power end of dc to dc converters have received less attention. One technique commonly used for higher power levels has been the full bridge topology operated with PWM control strategy. This topology offers a minimal voltage stress on the devices, and a low ripple current in the input and output capacitors. By increasing the switching frequency, the size and the weight of the reactive components are reduced. However the frequency achievable is limited by switching losses, transformer leakage inductance and output rectifier reverse recovery time. These factors constrain the maximum frequency, component size, and thus the power density achievable. Higher power densities have been achieved by operating full bridge topology in resonant mode. The reason for this being

that high power converters are still dominated by SCRs, and the most efficient way to reduce the switching loss is by terminating the conduction of the thyristors by placing them in resonant circuits. Power density of 1kW/kg has been reported with series resonant converters (SRC) at 10kHz. Converters of this type have been fabricated with power capabilities in the order of 100 kW [2]. But, the resonant operation also has its penalties such as frequency sensitivity, and higher voltage and current stress in the devices.

The dual active bridge converter has been proposed for high power dc to dc conversion in [4]. This voltage driven dc to dc converter consists of two inverting stages operating at a high frequency with controlled phase shift. This topology utilizes the leakage impedance of the coupling transformer as the energy transfer element. However, at high frequencies and high power levels the realization of the transformers with controlled leakage inductance is a challenging task. The soft switching control strategy proposed imposes severe limitations on the load range and allowed input voltage variations, in order to maintain soft switching on all the switches.

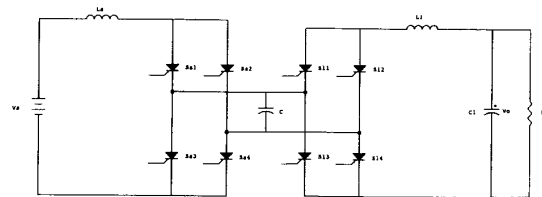


Fig.1 Single-phase IDC

A voltage source derivation of the inductor converter bridge (ICB) circuit [3], the inverse dual converter (IDC), shown in Figure 1, has been proposed in [1]. The dual active bridge converter proposed in [4] represents the dual of IDC. By suitable control the IDC topology provides buck-boost operation, without a transformer, and is capable of bidirectional power flow. In most applications where the load is a motor, isolation between motor load and dc bus is not necessary, because motor itself pro-

vides the electrical isolation that may be required in converters for safety or other reasons. For applications where dc isolation is required an ac link transformer can provide the necessary isolation. Since capacitive energy storage is much better than inductive energy storage in terms of per unit size and weight, capacitive energy transfer used in IDC is an important advantage to improve power density [7]. The ac link capacitor also provides the necessary commutation voltage across the switching devices, allowing the use of SCRs, at frequencies in excess of 20 kHz, without additional commutating circuits. Therefore, the power rating of the IDC can be scaled up to MW levels using well known high power SCR bridge technology. In most of the expected high power applications the use of SCR switches is a reliable and economical solution. However, in order to increase the operating frequency beyond 20 kHz devices such as MOS-controlled thyristors [5], IGBTs or G.T.O. thyristors [6] have to be considered. The combination of gate turn off and available commutation voltage will offer efficient switching at higher frequency and zero current.

The detailed analysis of the single phase IDC is given in [1]. A short review of the analysis is given as an introduction for the more sophisticated members of the IDC family.

### The Basic IDC

The operating waveforms of the single phase IDC with the load side bridge control angle leading ( power transfer from source to the load ) are shown in Figure 2. The switching sequence on the source side bridge is  $S_{S1}S_{S4}, S_{S2}S_{S3}, S_{S1}S_{S4}$  etc. and the same switching pattern is used on the load side. It has been shown that the average load power in a lossless single phase IDC converter is

$$\langle P \rangle = \frac{I_S I_L}{\omega C} \left( \phi - \frac{\phi^2}{\pi} \right) \quad 0 < \phi < \pi \quad (1)$$

where  $I_S$  and  $I_L$  are the average inductor currents,  $\omega$  is the angular frequency of the converter,  $\phi$  is the load side bridge advance angle and  $C$  is the link capacitor.

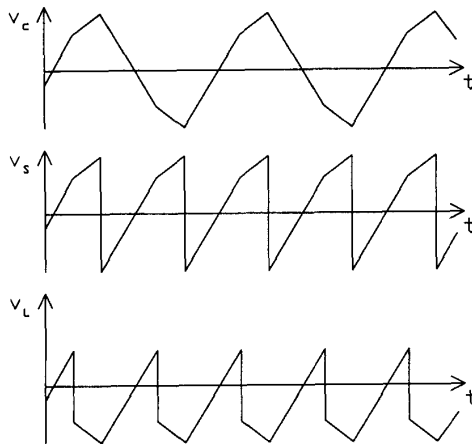


Fig.2 Waveforms associated with single-phase IDC; ac link capacitor voltage  $v_c$ , input and output choke voltage  $v_s$  and  $v_l$

By applying gyrator theory the dc gain has been found as

$$\langle \frac{V_o}{V_i} \rangle = \frac{\omega C}{\phi - (\phi^2/\pi)} R \quad (2)$$

where  $R$  represents the load resistance. The gain formula shows that the control of the IDC can be achieved by adjusting the phase and the frequency, or both. Both voltage step-up and step-down is possible continuously through a wide range without a need for a transformer. Various control strategies could be implemented, such as regulated output control, tracking output voltage control, constant output current control, constant load power control or constant input power. These strategies are application dependent and they subject of further research.

It has been shown in [1], that the single- phase IDC possesses several attractive features, such as

- buck-boost operation,
- bidirectional power processing,
- capacitive commutation of the switches,
- simple circuit implementation,
- small number of components,
- efficient high frequency operation,
- unlimited high power capability.

To further increase the power density, that is to decrease the component sizes, and decrease the device and component stresses in different applications, variations of the basic IDC are appropriate as described in this paper.

### Multiphase IDC

One way to produce a low input current ripple and output voltage ripple is the multiphase IDC. Figure 3 shows the three phase IDC. In exchange for additional switches the device and component stresses have been decreased ( Table 1 ), and the input and output filtering requirements are substantially lower when compared to single phase IDC. The converter in Figure 3 consists of two phase shifted, capacitor coupled, three phase inverter stages operating at a high frequency in six-step mode

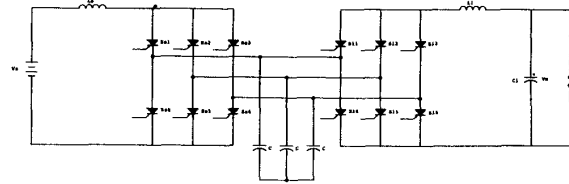


Fig.3 Three-phase IDC

The average power transferred from left to right for a lossless converter is

$$\begin{aligned} \langle P \rangle &= \frac{I_S I_L}{\omega C} \left( 2\phi - \frac{3\phi^2}{2\pi} \right) & \text{for } 0 < \phi < \frac{\pi}{3} \\ \langle P \rangle &= \frac{I_S I_L}{\omega C} \left( 3\phi - \frac{3\phi^2}{\pi} - \frac{\pi}{6} \right) & \text{for } \frac{\pi}{3} < \phi < \frac{2\pi}{3} \\ \langle P \rangle &= \frac{I_S I_L}{\omega C} \left( \phi - \frac{3\phi^2}{2\pi} + \frac{\pi}{2} \right) & \text{for } \frac{2\pi}{3} < \phi < \pi \end{aligned} \quad (3)$$

| Factors of comparison | Single phase IDC | Three phase IDC |
|-----------------------|------------------|-----------------|
| Power rating          | 100kW            | 100kW           |
| Output voltage        | 270V             | 270V            |
| Input voltage         | 28V              | 28V             |
| Control angle         | 40               | 40              |
| Output voltage ripple | 1%               | 1%              |
| Number of switches    | 8                | 12              |
| Peak voltage          | 800V             | 525V            |
| Switch rms current    | 2.4kA/250A       | 2kA/200A        |
| AC link capacitor     | 22μF             | 50μF            |
| Cap.peak voltage      | 800V             | 275V            |
| Cap. rms current      | 3500A            | 3500A           |
| Input choke           | 5.5μH            | 0.55μH          |
| Ind.voltage           | 800V             | 250V            |
| Peak ind.current      | 3200A            | 3200A           |
| Output choke          | 26μH             | 2.3μH           |
| Ind.voltage           | 800V             | 200V            |
| Peak ind.current      | 395A             | 395A            |
| Filter cap.           | 50μF             | 8μF             |

TABLE I. The comparison of single-phase IDC and three-phase IDC

The gain of the three-phase IDC is given by

$$\begin{aligned}
 \left\langle \frac{V_o}{V_i} \right\rangle &= \frac{\omega CR}{2\phi - (3\phi^2/2\pi)} \quad \text{for } 0 < \phi < \frac{\pi}{3} \\
 \left\langle \frac{V_o}{V_i} \right\rangle &= \frac{\omega CR}{3\phi - (3\phi^2/\pi) - (\pi/6)} \quad \text{for } \frac{\pi}{3} < \phi < \frac{2\pi}{3} \\
 \left\langle \frac{V_o}{V_i} \right\rangle &= \frac{\omega CR}{\phi - (3\phi^2/2\pi) + (\pi/2)} \quad \text{for } \frac{2\pi}{3} < \phi < \pi
 \end{aligned} \quad (4)$$

It can be shown from Eqn.(2) and Eqn.(4) that the ac link capacitor required per phase for the three-phase topology is twice the value of that required for the single-phase IDC of the same power. But since the current and voltage of the capacitor has been decreased the size and weight of these capacitors is smaller. By maintaining the same ripple current through the source and load inductors, the inductors will be approximately an order of magnitude smaller than in the single-phase counterpart. The peak voltage across the switches is decreased six times. Overall, for the same power level the three phase IDC is significantly smaller than the single-phase IDC. A comparison between these converters has been shown in Table 1 for boost operation. Furthermore the reliability of the converter has been increased since in case of a switch failure the three-phase converter can make a transition to a single-phase operation by providing the appropriate means of control.

### The Transformer Coupled IDC

In order to achieve dc isolation and lower device stresses the transformer coupled IDC can be implemented. This configuration, shown on Figure 4a, will reduce the rating of the input bridge converter switches. Since the ac voltage rating of the capacitors at high frequencies is a critical factor this topology provides the benefit of voltage rating reduction of the link ca-

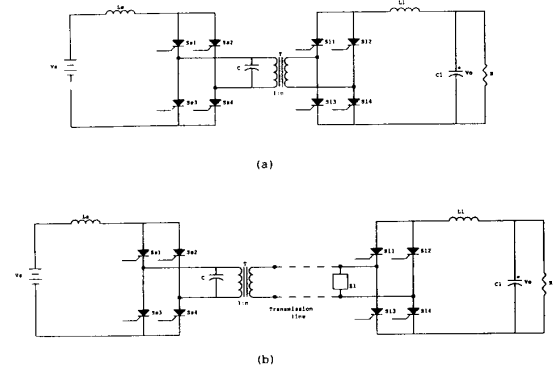


Fig.4 (a) Transformer coupled IDC

(b) IDC with integrated transmission line

The parallel distribution of IDC bridges for two loads is shown in Figure 6. Both topologies are capable of supporting individually regulated buck-boost operation for isolated loads. Regenerating loads can augment the source converter in supplying the other load. Furthermore, the source and loads could be placed in pacitor for the same output voltage. The design of this converter requires additional attention in order to avoid possible undesirable resonant effect between the ac link capacitor and magnetizing inductance of the transformer. The transformer coupled concept is naturally expandable to an ac power transmission line linking the source and the load ( Figure 4b ). The transmission voltage magnitude can be as high as required, independently of the input voltage, furthermore, the voltage magnitude and phase can be controlled to accommodate system operational constraints. Although it provides some advantages, integration of the transmission line into the IDC design does not necessitate a transformer.

### Power Distribution Topologies

For high power applications where several dc loads are served, and output regulation is required two topologies are examined. The serially connected IDC's for two loads is shown in Figure 5, where the individual bridges could be single or multi phase, suitable for a converter with multiple regulated outputs.

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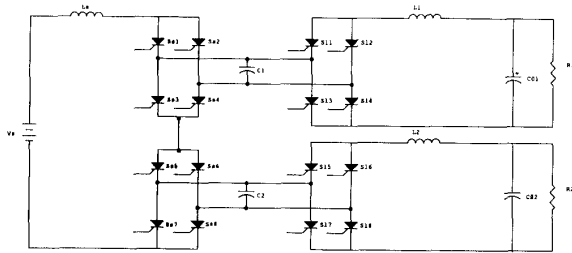


Fig.5 Serially connected IDCs

different sites, by providing a high frequency ac transmission line between them. The advantages of high frequency ac power distribution from the standpoint of reduced size and weight of magnetic components and with regard to filtering requirements

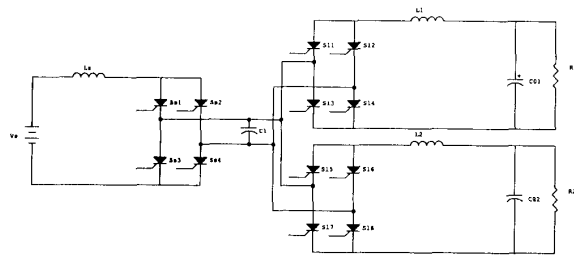


Fig.6 IDCs connected in parallel

are well established [8]. Unlike the parallel distribution scheme the serially connected IDC provides a fully independent control of the individual converters. Both phase and frequency control strategies can be applied to each serial IDC. The advantage of using phase and frequency control at the same time is elaborated in following. The gain curve of a single phase IDC is shown in Figure 7. As seen from this figure, the gain is very sensitive to

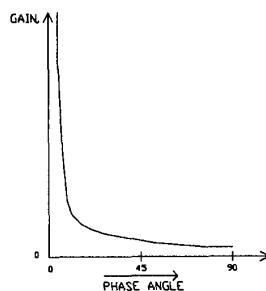


Fig.7 Gain curve

phase variation  $\phi$  for lower values of the operating angle. When the angle control enters the sensitive range frequency control provides new operating limits for phase control with desired sensitivity and gain. This can be derived also from the Eqn.(2) by solving the equation for phase  $\phi$ ,

$$\phi = \frac{\pi}{2} \left( 1 + \sqrt{\frac{1 - 8fC}{< V_o/V_i >}} \right) \quad (5)$$

This equation shows that if we want to operate at higher loads which are maybe beyond the phase control region the frequency could be changed in order to get a stable operating point.

Furthermore, substantial input ripple current reduction can be achieved by controlling the upper bridge phase angle in respect to the lower bridge switching pattern when both bridges operates at same frequency.

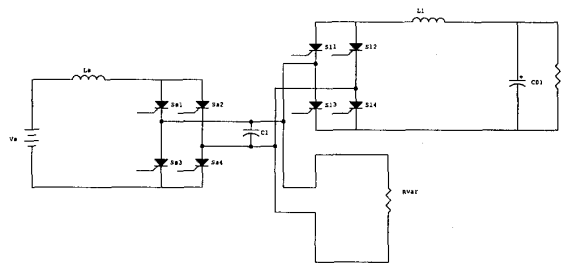


Fig.8 AC tapping of the IDC

For applications where ac and dc loads are present the scheme shown on Figure 8 will be optimal. Simulation results have shown that ac link can be loaded to more than 50% of the overall converter rating and still allow regular operation of the converter. When both frequency and phase are used to control the dc gain then the tapped ac resistive load is unregulated. However, if only the phase is varied in order to adjust the gain, frequency control may be applied to control the ac voltage with the penalty of limited operating range.

## Conclusion

Several topological variations of the inverse dual converter have been presented for high power applications. These topologies have most of the IDC features such as buck-boost operation, bidirectional power processing, capacitive commutation for switches, and unlimited high power capability.

The multiphase, the transformer coupled and the power distribution IDC topologies offer some additional properties such as significant power density improvement, isolation, ac tapping, and input current reduction.

A quantitative comparison between the single and the multiphase IDC has been also presented.

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