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A Review on Power Factor Correction DC/DC Converters for Brushless Dc Motor Drives

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ABSTRACT

This paper explains the detailed classification of power factor correction(PFC) DC/DC converters. PFC DC/DC converters are categorized into Non-isolated and Isolated type; based on the use of a High Frequency Transformer isolating the output side from the input side. Non-isolated converter topologies have the advantages like light weight & small size; at the cost of higher number of components. Isolated topology provides high-frequency isolation of the output from the input, and voltage scaling benefits; by employing a high-frequency transformer between the power stage and the output side. Thus, the cost of this converter topology is high. Non-isolated topologies are categorized as: Buck, Boost, Buck-boost, Cuk, SEPIC, Zeta, Luo, Canonical Switching Cell, (CSC), Landsman and Sheppard Taylor converters; whereas, Isolated converter topologies are categorized as: Flyback, Forward, Isolated Buck, Isolated Boost, Isolated Buck-Boost, Isolated Cuk, Isolated SEPIC, Isolated Zeta, Isolated Luo, Isolated CSC, and Isolated Landsman converter. Non-Isolated & Isolated converter topologies are further classified into Bridged[1] and Bridgeless converters, depending on the use of a Diode Bridge Rectifier (DBR) in the circuit. IHQRR is another type of DC/DC converter that integrates two converter topologies, and hence provides the benefits of improved power quality, reduced switching losses, higher efficiency and performance similar to that of single-stage converters. Choice of a PFC converter topology relies upon the efficiency, size, weight application, and cost of the converter. Choice of the operational mode of a PFC converter is actually a trade-off between the switching stresses and the cost.

KEYWORDS: Brushless DC Motor, DC/DC Converter, Power Factor Correction, Discontinuous Conduction Mode, Continuous Conduction Mode.

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1. INTRODUCTION

Conventional BLDC motor drives are fed from a diode bridge rectifier[6,8,21](DBR), filter capacitor and a Voltage Source Inverter (VSI)[8,16,21]. Drive speed is regulated by altering the switching sequence of the VSI. Here, the dc-bus voltage is kept constant, and the drive speed is regulated by variable frequency switching of the VSI, i.e., by controlling the frequency of the source voltage fed to the BLDC motor[8]. The dc-bus capacitor charges whenever voltage of the dc-bus, V_{dc} falls below the supply voltage, V_s during one cycle of the source voltage. Thus, the charging current of the dc-bus capacitor, C_d is pulsating in nature[6]. This source current is abundant in harmonics, having a high Total Harmonic Distortion, high Crest Factor[1,8] and a low Power factor. This in turn causes a voltage distortion. High-frequency switching of the six VSI switches causes increased switching losses, decreasing the efficiency of the VSI. As the conduction losses and switching losses of the VSI switches increase, the overall efficiency of the drive system is decreased. Also, controlling the switching sequence of the VSI switches for regulating the motor speed increases the complexity of the control circuit. Thus, PFC circuits are employed to enhance the power factor to unity[1,8].

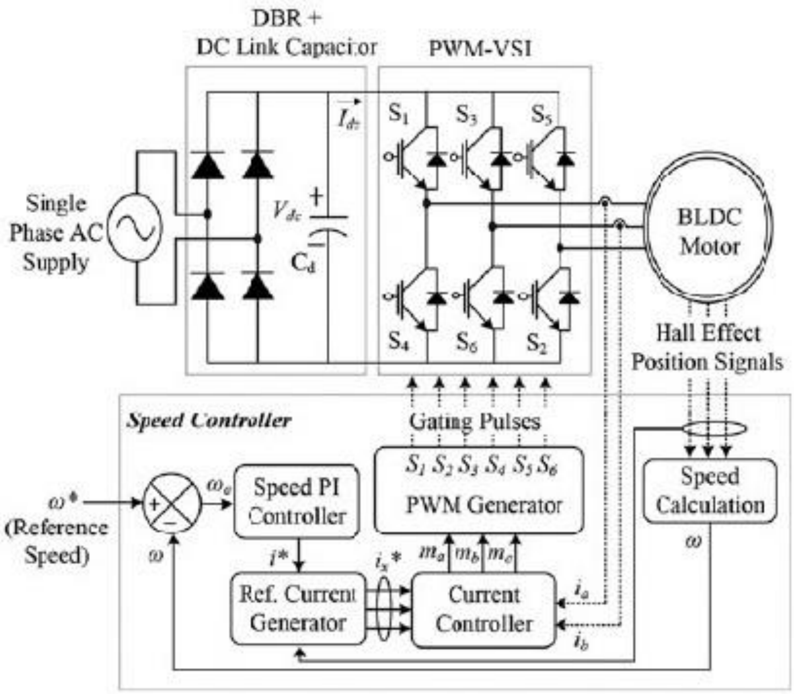

Figure 1. A conventional BLDC motor drive

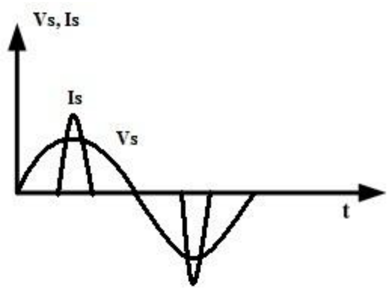

Figure 2. Source voltage and source current waveforms drawn by the filter capacitor[3]

PFC circuits are basically DC/DC voltage regulator circuits, usually connected between the output of the diode bridge rectifier and the input side of the VSI. These circuits regulate the dc-bus[1] voltage, and force the input current to be in-phase with the supply voltage; thus attaining a unity power factor at the supply side. This self-PFC[2] capability of these PFC converters is possible due to the innate characteristics of their topologies.

PFC converters can operate in two modes:

i) Continuous Conduction Mode[1] (CCM)
ii) Discontinuous Conduction Mode[1] (DCM)

i) Continuous Conduction Mode (CCM)-As the name suggests, in this operational mode, the inductor current or the capacitor voltage remains continuous and at no time falls to zero over a complete switching cycle. The main highlight of this mode is that it uses Current Multiplier Approach[8], which requires two current sensors to detect the line currents and one voltage sensor to detect the dc-bus voltage. Thus, by shelling out more pennies, it is possible to reduce the voltage and current switching stresses on the converter switch. This mode is used for high-power[1,6,8] applications due to its reduced switching stress capability.

ii) Discontinuous Conduction Mode (DCM) – In this mode, the inductor current or the capacitor voltage reaches zero and becomes discontinuous over a complete switching cycle. The main highlight of this mode is that, it works on Voltage Follower[8] approach, which requires only one voltage sensor to detect the dc-link voltage. Hence, it is cheaper and attains inherent power factor at the ac mains; imposing a higher voltage and current switching stress on the PFC converter switch. Hence, this mode is preferred only for medium and low power[1,6,8] applications where switching stresses can be compromised.

Choice of the topology of a PFC converter relies upon the efficiency, size, weight, cost and application, of the converter[1,2,3,26]. And, the choice of the operational mode of a PFC converter is typically a trade-off between the switching stresses and the cost[1,2,3,26]. This paper deals with categorization of various PFC converter circuits.

2. CLASSIFICATION OF PFC DC/DC CONVERTERS

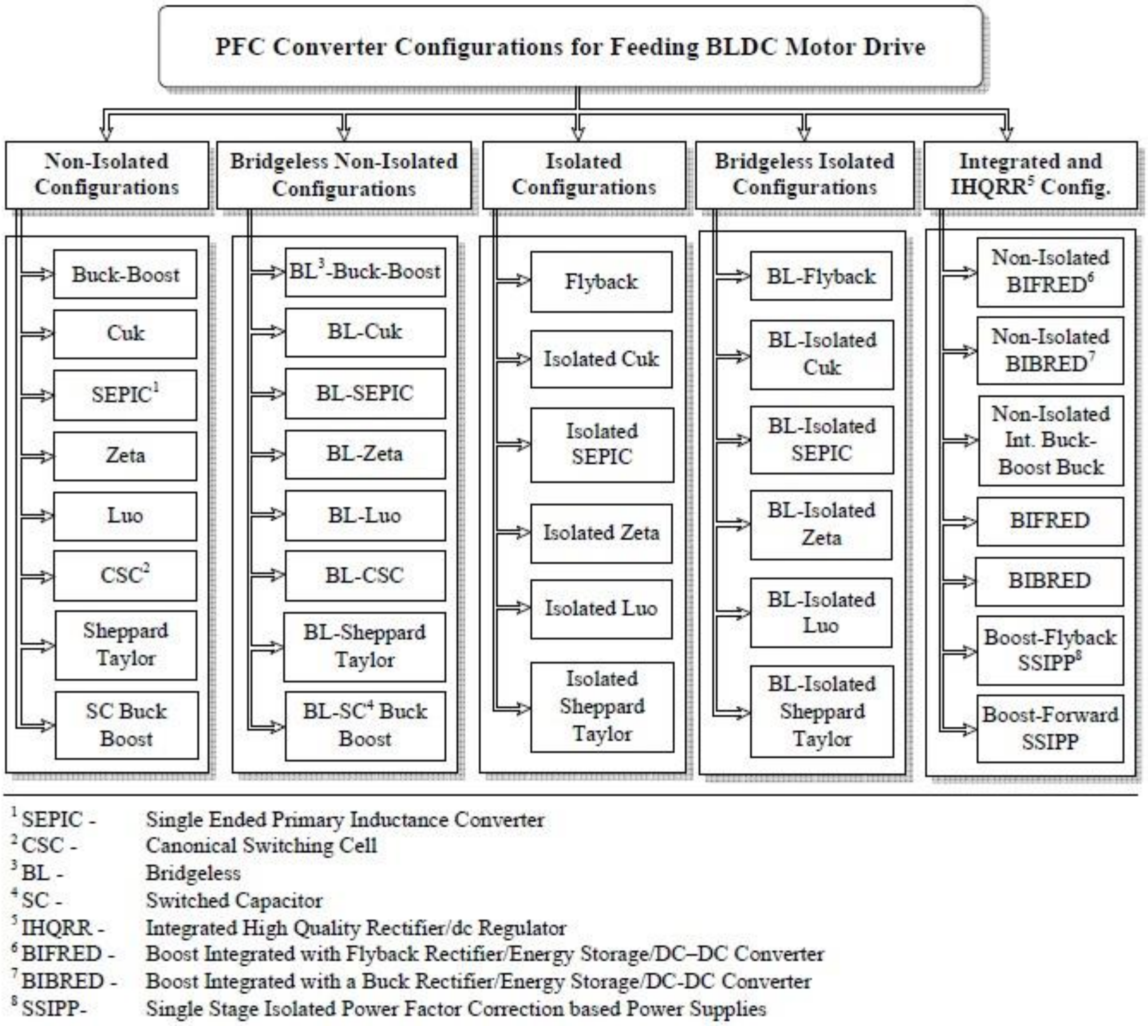

Figure 3. Classification of PFC DC/DC converters[1]

This paper explains a detailed review on the classification of Power Factor Correction DC/DC converters. Power Factor Correction DC/DC converters are sub-divided into three categories[1] namely, Non-Isolated DC/DC Converters, Isolated DC/DC Converters, and Integrated High Quality Rectifiers (IHQRR). Each category of DC/DC converter is dealt in detail below.

2.1 Non-Isolated DC/DC converters

Non-isolated DC/DC converters are used in applications where galvanic isolation[27] is not required between the power stage and the output side. Hence, these converters do not require a high frequency transformer[3] separating the input and output stages in their topologies. Main highlights of Non-Isolated Converter topologies include:

- Decreased component count
- Simple Design

- Light-weight & compact size
- Economical

Limitations of Non-Isolated Converter topologies include:

- These converters are not preferred in domestic applications like refrigerators which demand a galvanic isolation between the input and output stages
- Suffer from efficiency issues at low power levels.

Non-Isolated converters are further classified into:

- Bridged Non-Isolated Converters
- Bridge-less Non-Isolated Converters

depending on whether a diode bridge rectifier[6,8,21] (DBR) is included in the circuit or not.

2.1.1 Bridged Non-Isolated DC/DC converters

Various topologies of Bridged Non-Isolated DC/DC converters include: Buck[1], Boost[1,4,5], Buck-boost[1,6,7], Cuk[8,9], SEPIC[10,11,12], Zeta[13,14], Luo[15], Canonical Switching Cell,[16,17](CSC), Landsman[18], Sheppard Taylor[19,20] and Switched Capacitor Buck-Boost[28] converters. The Buck converter provides an output voltage, V_o lower than the input DC voltage,V_{in} given by:

$$\mathrm{V_o} = D * V_{in} \tag{1}$$

Where, D denotes the duty ratio of the converter, such that, $0 < D < 1$. Boost converter provides an output voltage, V_o greater than the input DC voltage,V_{in} given by:

$$\mathrm{V_o} = \left(\frac{1}{1-\mathrm{D}}\right)\mathrm{V_o} \tag{2}$$

Buck-boost[1,6,7], Cuk[8,9], SEPIC[10,11,12], Zeta[13,14], Landsman[18], Switched-Capacitor Buck-Boost[28], and Canonical Switching Cell,[16,17](CSC) converters provide either step-up or step-down of the input DC voltage. The output voltage, V_o of these converters is given as:

$$\mathrm{V_o} = \left(\frac{\mathrm{D}}{1-\mathrm{D}}\right) * \mathrm{V_{in}} \tag{3}$$

These converters possess salient features which include:

- Excellent dynamic performance
- Enhanced light-load efficiency
- Excellent light-load voltage regulation capability

A Canonical Switching Cell (CSC)[16,17] converter has a lower component count, lower conduction losses, and excellent light-load voltage regulation capability; while a Sheppard Taylor converter overcomes the problems of Control Detuning[1,18,19,20]. Buck-Boost converter has least component count, but has high input and output current ripple. Landsman converter; a modified CSC converter[18] with an output inductor overcomes this problem with reduced output current ripple[29]. Sheppard Taylor and Switched-Capacitor Buck-Boost converters are typically preferred for power factor correction at AC mains. Luo[15] converter which has inherent characteristics of voltage lifting[15], provides excellent voltage regulation over a wide range of DC voltages and excellent light-load efficiency[15].

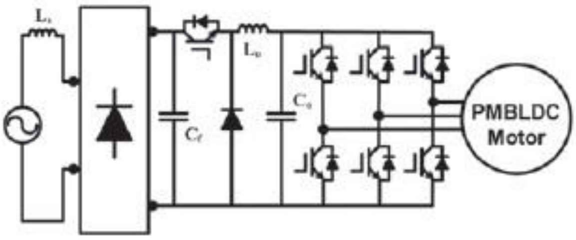

Figure 4. A Buck PFC converter-fed BLDC motor drive[30]

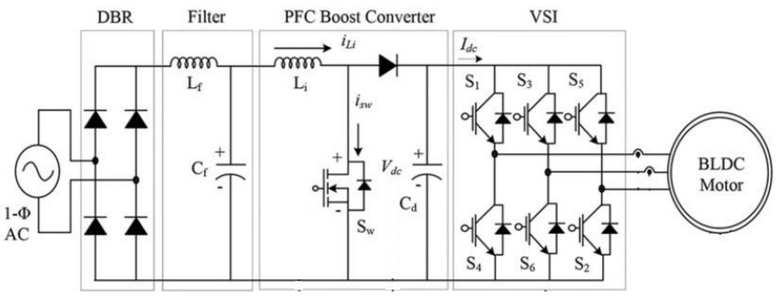

Figure 5. A Boost PFC converter-fed BLDC motor drive

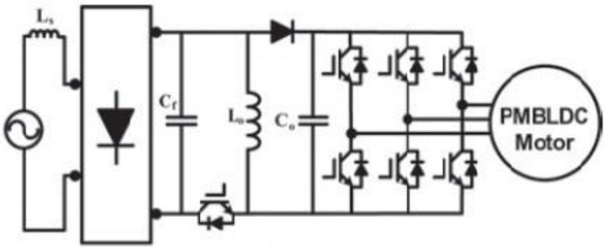

Figure 6. A Buck-Boost PFC converter-fed BLDC motor drive [30]

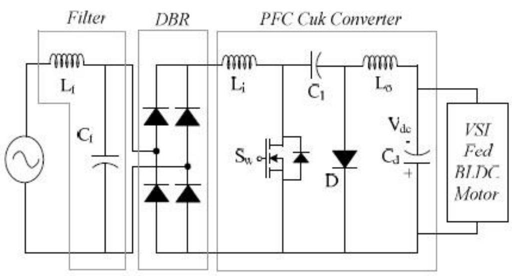

Figure 7. A Cuk PFC converter-fed BLDC motor drive[1,8]

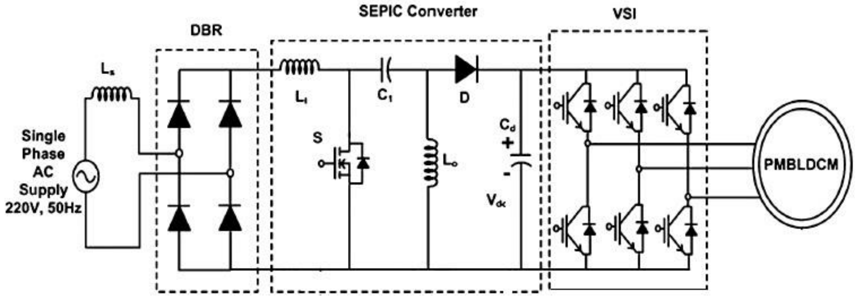

Figure 8. A SEPIC PFC converter-fed BLDC motor drive[11]

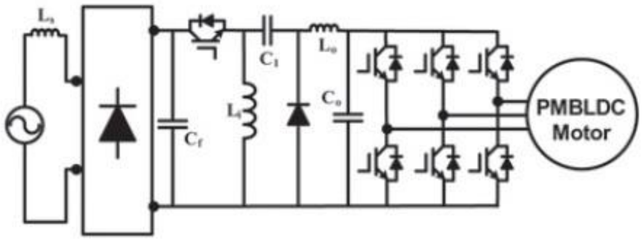

Figure 9. A Zeta PFC converter-fed BLDC motor drive[30]

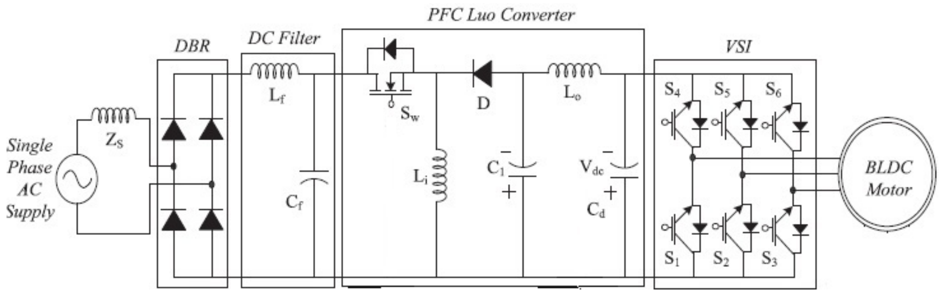

Figure 10. A Luo PFC converter-fed BLDC motor drive[15]

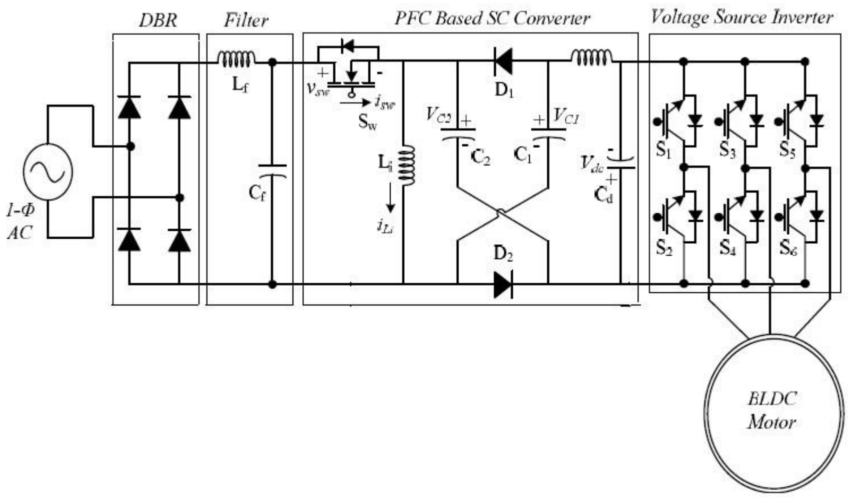

Figure 12. A Switched Capacitor Buck-Boost PFC converter-fed BLDC motor drive [28]

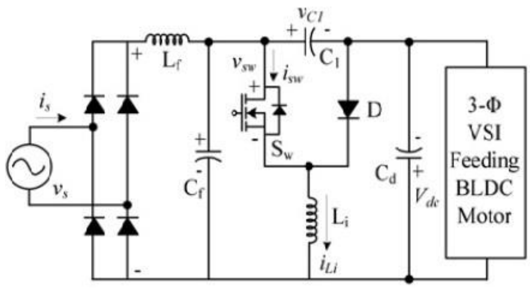

Figure 13. A Canonical Switching Cell (CSC) converter-fed BLDC motor drive [18]

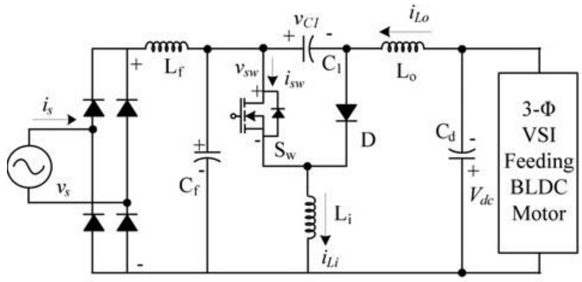

Figure 14. A Landsman PFC converter-fed BLDC motor drive [18]

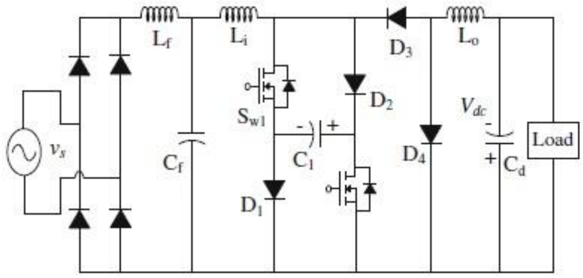

Figure 15. A Sheppard Taylor PFC converter-fed BLDC motor drive [19]

2.1.2 Bridge-less Non-Isolated DC/DC converters

Bridge-less configuration offers the advantage of the complete or partial elimination[1] of the diode bridge rectifier, thus minimizing conduction losses of the diodes, at the cost of a higher number of components.

Highlighting features of Bridge-less Non-Isolated DC/DC Converters include:

- Lower number of conducting components in a half-cycle
- Reduced conduction losses
- Increased efficiency of the converter

Limitation of this converter includes:

- Higher number of components involved
- Requires expensive and complex isolated gate drivers

Various topologies of Bridge-less converters include Bridge-less Buck-Boost[6], Bridge-less Cuk[31], Bridge-less Zeta[32], Bridge-less SEPIC[33,34], Bridge-less Landsman[35], Bridge-less CSC[36], Bridge-less Luo[37], Bridge-less Switched-Capacitor Buck-Boost and Bridge-less Sheppard Taylor converters[38]. Bridge-less Buck-Boost has minimum number of components and features highest efficiency amongst all the other bridgeless topologies. Bridge-less Cuk[31] and Bridge-less SEPIC[33,34] provides enhanced power quality at the AC mains.

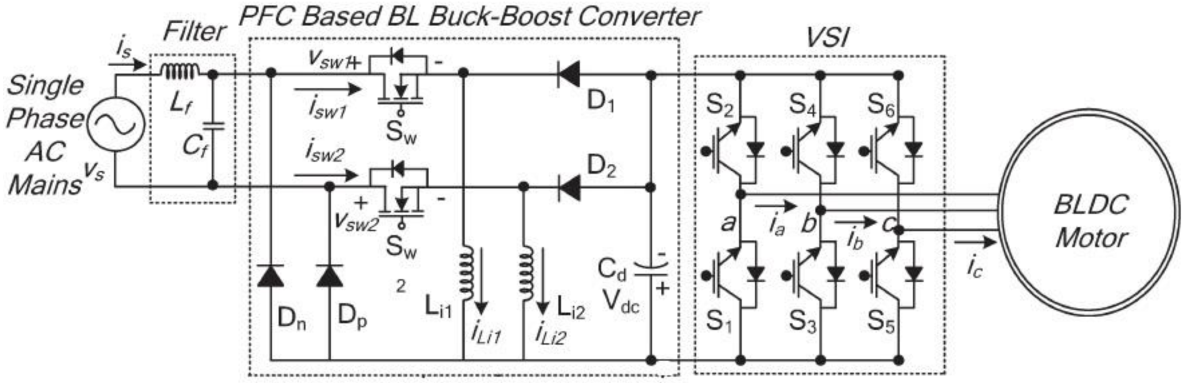

Figure 16. A Bridgeless Buck-Boost converter-fed BLDC motor drive [6]

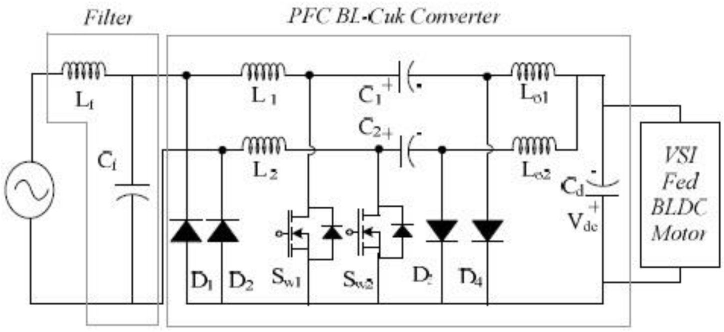

Figure 17. A Bridge-less Cuk converter-fed BLDC motor drive [1]

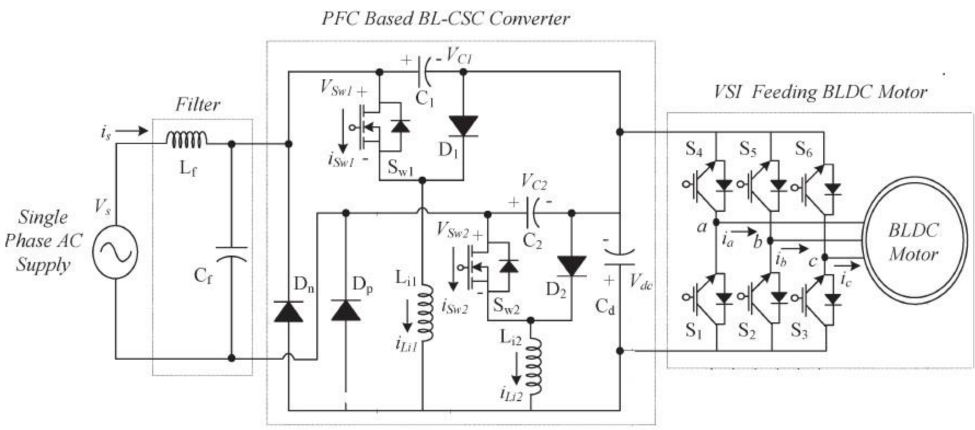

Figure 18. A Bridge-less CSC converter-fed BLDC motor drive [36]

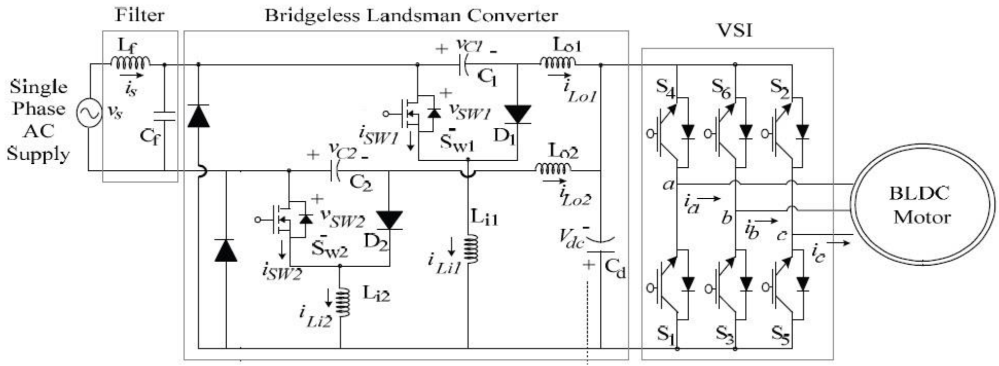

Figure 19. A Bridge-less Landsman converter-fed BLDC motor drive [35]

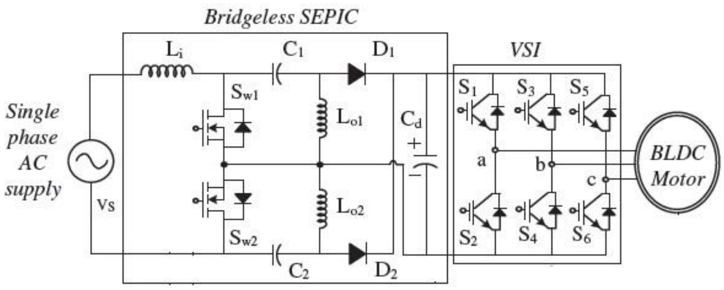

Figure 20. A Bridge-less SEPIC converter-fed BLDC motor drive [33,34]

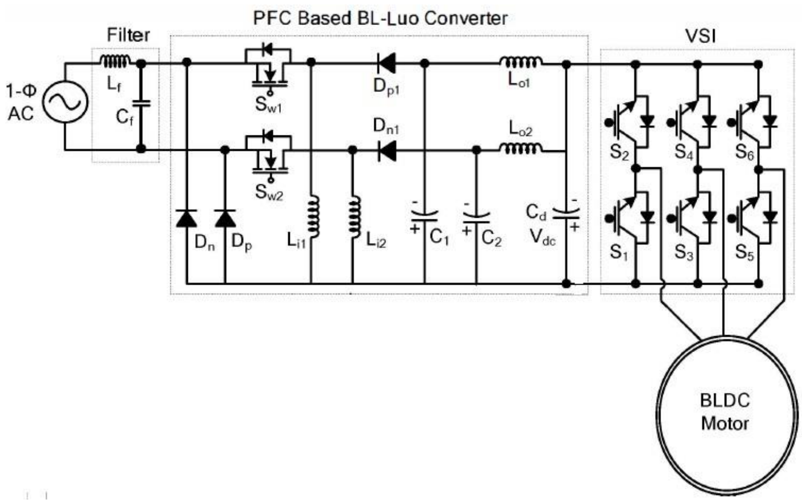

Figure 21. A Bridge-less Luo converter-fed BLDC motor drive [37]

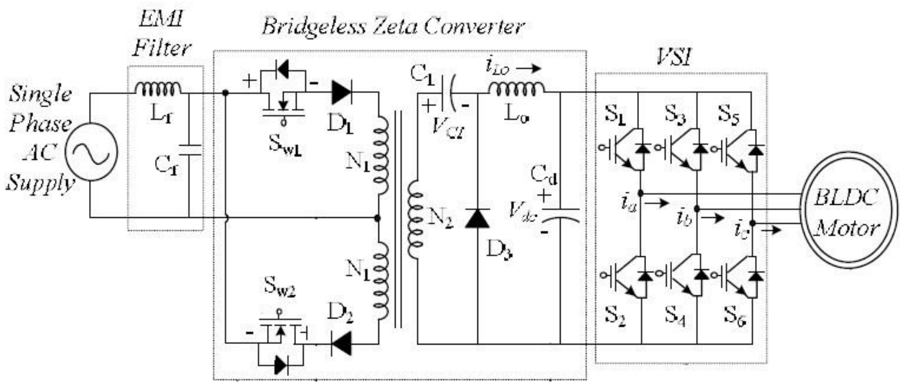

Figure 22. A Bridge-less Zeta PFC converter-fed BLDC motor drive[32]

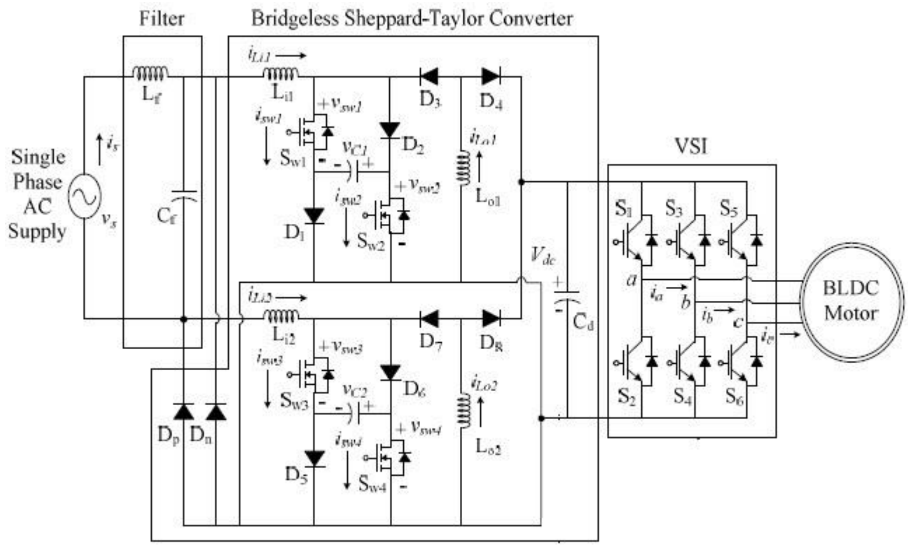

Figure 23. A Bridge-less Sheppard Taylor PFC converter-fed BLDC motor drive [38]

2.2 Isolated DC/DC converters

In these converters, a High Frequency Transformer (HFT) is added between the power stage and the output side[2]. This provides the advantages of electrical isolation between input and output stages, voltage scaling, minimization of stresses in switching devices, and provision of multiple outputs in multi-output connections[3]. The isolated DC/DC converters are classified into:

- Bridged Isolated DC/DC Converters
- Bridgeless Isolated DC/DC Converters

depending on whether a full- bridge diode rectifier is included in the circuit or not.

2.2.1 Bridged Isolated DC/DC converters

Various topologies of the Bridged Isolated DC/DC converters include Isolated Buck, Isolated Boost, Isolated Buck-Boost, Isolated Cuk[1], Isolated SEPIC, Isolated Zeta[39], Isolated CSC, Isolated

Landsman, Isolated Luo[40] and Isolated Sheppard Taylor[19] converters, Flyback[3] Converter and Forward Converter. These converters provide enhanced power factor at the source side, low source current THD and reduced output voltage ripple[3].

A Flyback[3] converter has the minimum component count, but has higher stress on the PFC converter switch. Hence, it is preferred for low-power[1,3]applications (100-150W) only. The main limitation of Flyback[3] converter is the problem of leakage inductance, which introduces a cap on its rating. Isolated configurations of Cuk[1], Zeta[39], SEPIC converters are employed for high-power applications. Isolated Sheppard Taylor[19] converter overcomes the problems of control detuning of BLDC motor drives. Isolated Luo[40] converter enhances power quality at the source-side of the drive. Output voltage, V_o of Isolated Buck-Boost, Isolated Cuk[1], Isolated SEPIC, Isolated Zeta[39], Flyback[3] converters are given by:

$$V_O = \left(\frac{N_2}{N_1}\right) * \left(\frac{D}{1-D}\right) * V_{in} \tag{4}$$

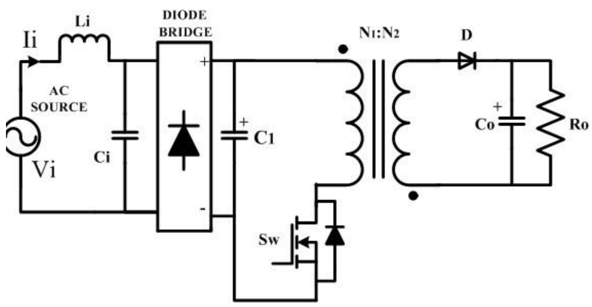

Figure 24. A Flyback converter[3]

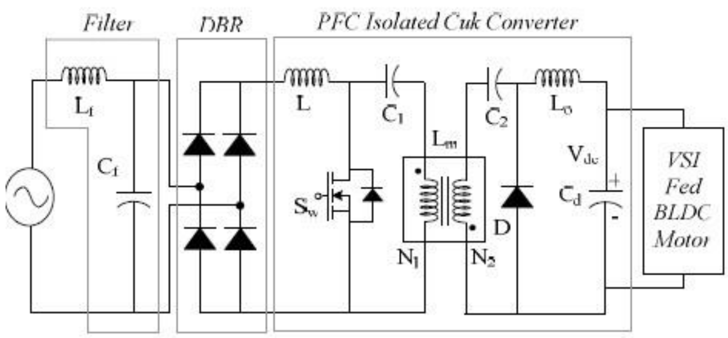

Figure 25. An Isolated Cuk converter-fed BLDC motor drive [1]

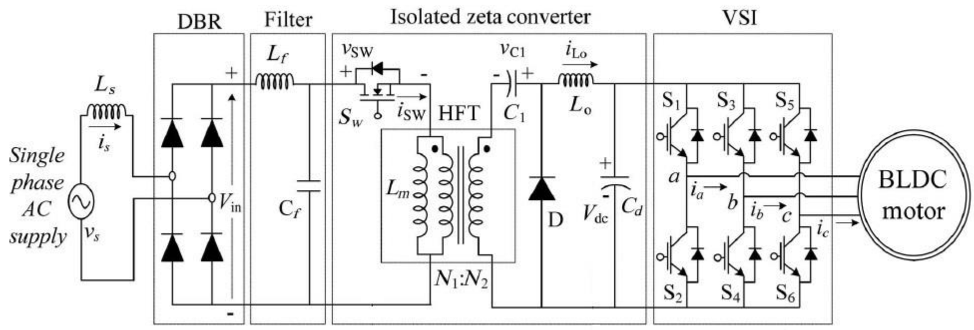

Figure 26. An Isolated Zeta converter-fed BLDC motor drive [39]

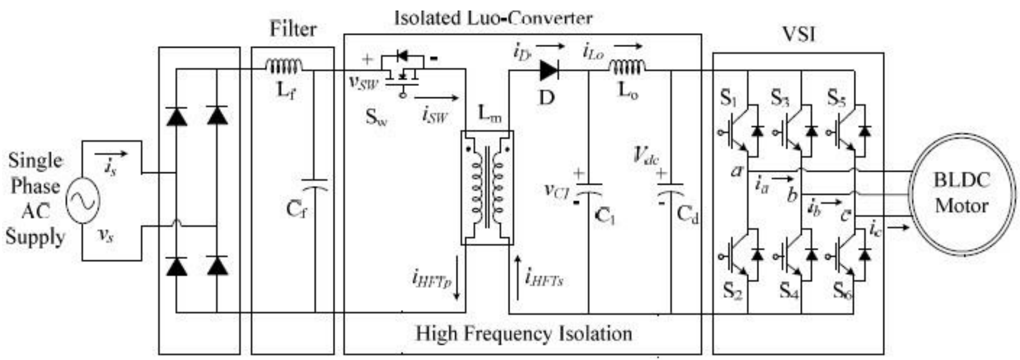

Figure 27. An Isolated Luo converter-fed BLDC motor drive [40]

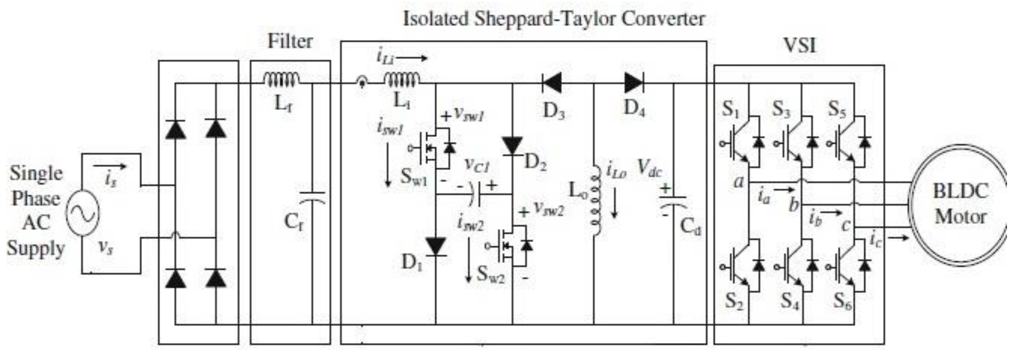

Figure 28. An Isolated Sheppard Taylor converter-fed BLDC motor drive [19]

2.2.2 Bridge-less Isolated DC/DC Converters

These converters integrate the salient features of the bridge-less configuration with high frequency isolation[2]. Thus, the conduction losses at the source side of these converters are considerably reduced. Hence, these converters are utilized for improving power quality at the AC mains. A limitation of this converter is that, it suffers from efficiency issues due to the losses in the high frequency transformer[3].

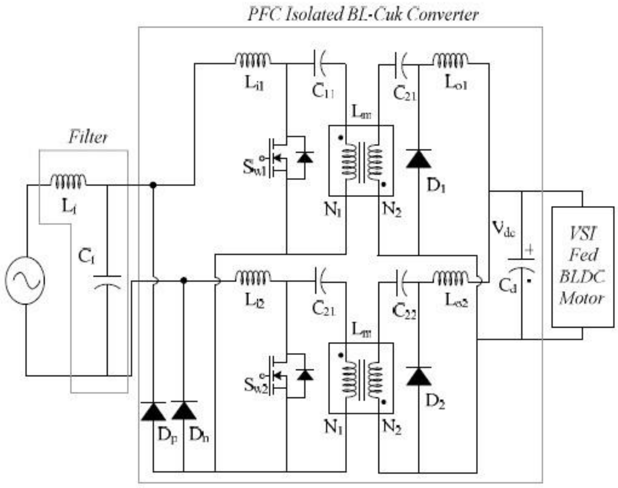

Figure 29. An Isolated Bridge-less Cuk converter-fed BLDC motor drive [1,41]

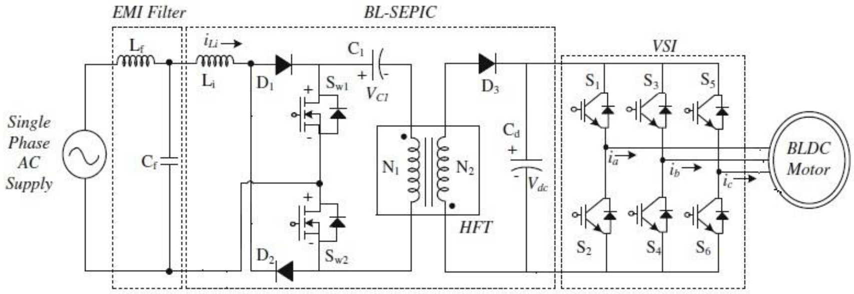

Figure 30. An Isolated Bridge-less SEPIC converter-fed BLDC motor drive [42]

2.3 Integrated and High Quality Rectifiers (IHQRR)

IHQRR[1,24,25] combines two converters for attaining an improved power quality at the AC mains. These converters incorporate a single switch which offers reduced switching losses, and thus possess high efficiency and performance similar to that of a single-stage converter[1,24,43]. The main features of these converters include:

- Excellent dynamic response
- High light-load voltage regulation capability
- High light-load efficiency

The main limitation of these converters is large component count in their topologies. IHQRRs are classified into two sub-categories namely:

(i) BIFRED[1,42] Converter–Boost Integrated Flyback Energy-Storage DC Converter

(ii) BIBRED1,[43]Converter–Boost Integrated Buck-Rectifier Energy Storage DC Converter

(iii) Integrated Buck-Boost Buck Converter[44]

(iv) Boost-Flyback Single Switch Isolated Power Factor Correction based Power Supplies (Boost-Flyback SSIPP)[25]

(v) Boost-Forward Single Switch Isolated Power Factor Correction based Power Supplies (Boost-Forward SSIPP)[24]

These converters can be further classified into Isolated and Non-Isolated[1,2] converters. BIFRED is an IHQRR that integrates Boost PFC converter with a Flyback converter using a switch[26]. The Boost converter in DCM operates as an innate PFC, whereas, the Flyback converter is allowed to operate in DCM or CCM, based on the requirement. The main features of a BIFRED Converter include:

- Simplicity, due to single switch and single control loop and isolation
- One-time processing of a small part of output power

In a BIFRED[1,42] converter, the combination of DCM Boost and CCM Flyback, converter, increases the voltage on the storage capacitor significantly, and is load dependent. This is the main limitation of a BIFRED Converter. BIBRED[1,43] converter has the following advantages:

- Inherent power factor correction
- Reduction in size of the high frequency transformer due to low value of magnetizing inductance, L_m.

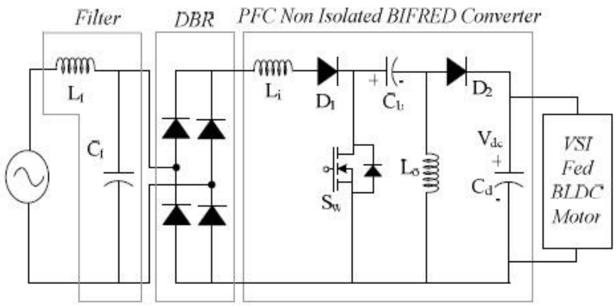

Figure 31. A Non-Isolated BIFRED converter-fed BLDC motor drive [1]

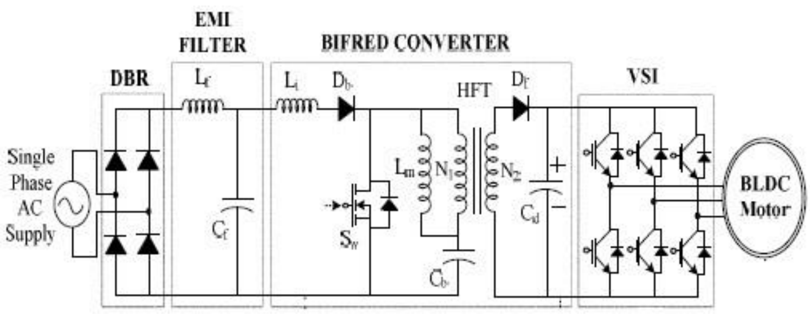

Figure 32. An Isolated-BIFRED converter-fed BLDC motor drive [43]

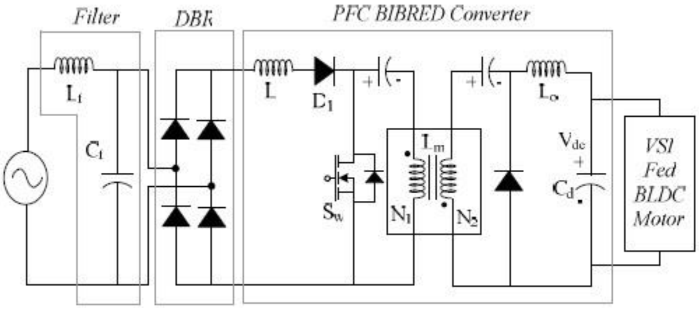

Figure 33. A BIBRED converter-fed BLDC motor drive [1,44]

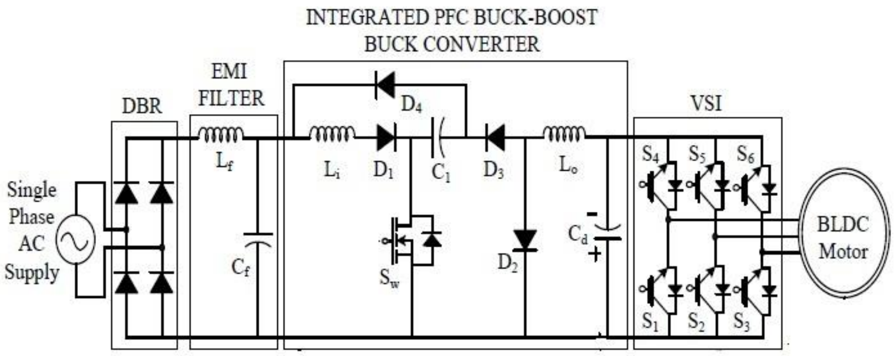

Fig. 34. An Integrated PFC Buck-Boost Buck converter-fed BLDC motor drive[45]

A non-isolated Integrated Buck-Boost Buck[45] converter is a PFC converter that combines a Buck-Boost converter and a Buck converter. It features a soft switching for reduced losses in the PFC converter switch[1].

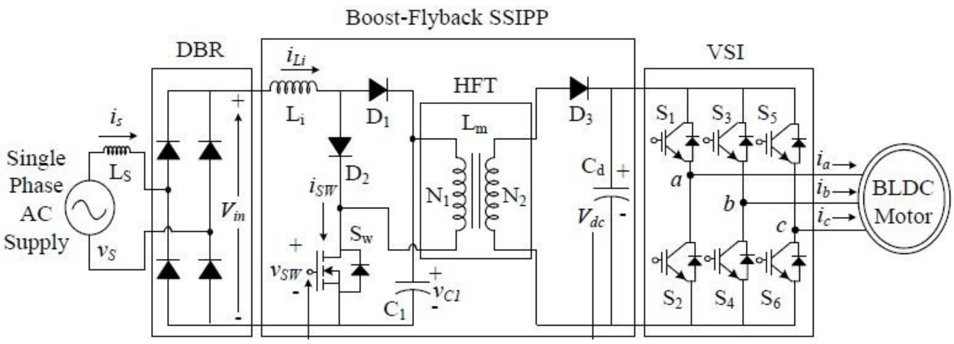

Figure 35. A Boost-Flyback SSIPP PFC converter-fed BLDC motor drive[25]

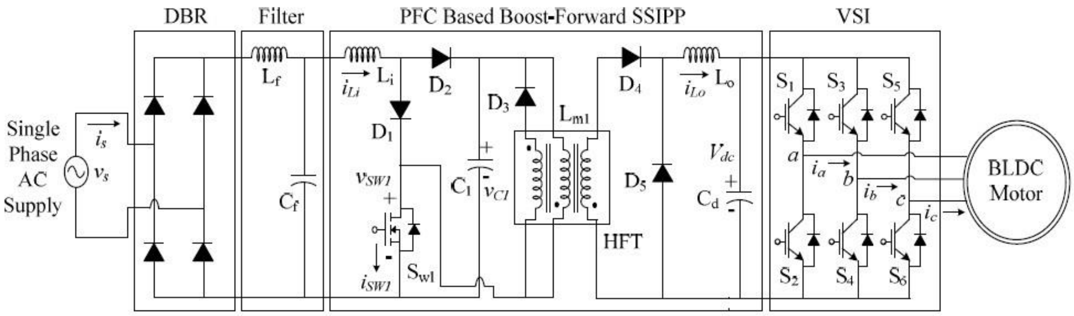

Figure 36. A Boost-Forward SSIPP PFC converter-fed BLDC motor drive[24]

3. FUTURE PROSPECTS

With the rapid developments in the fields of semiconductor switching devices[46], super-fast micro-processors, digital control strategies, it is possible to develop efficient switching mechanisms, with reduced conduction and switching losses in the converters. Researches to develop new magnetic materials with comparatively higher flux densities can lead to the production of compact and highly efficient permanent magnets for BLDC motors[47]. Utilization of highly sophisticated softwares like MagNet[1], Motor-Solve[1], SPEED[1] etc for the geometric design, aids in the development of highly energy-efficient BLDC motors. Wide band-gap devices can be used to improve the efficiency and speed of switching devices. Integration of different converter configurations[48,49] helps develop topologies that can enhance the power quality and effectively correct the power factor simultaneously. Integration of several areas of active research, like artificial intelligence, fuzzy logic, neural networks and Internet Of Things (IOT) and Big Data into the existing digital control strategies[50,51] will help develop new and faster switching schemes for the switching devices. Sensor-less control strategies opted for the control of BLDC motors can effectively reduce the overall drive cost on account of the reduction in sensors, and improves the drive performance in hazardous atmospheres.

4. CONCLUSION

Power Factor Correction converters have self PFC capability and provide excellent dc-bus voltage control over a broad speed range. This paper summarizes a broad classification of PFC converters. Non-Isolated topologies are preferred for low-cost and light weight applications, where the switching stresses can be compromised to attain economy. Isolated topologies are typically preferred for applications requiring a galvanic isolation, like refrigerators. Each of these topologies is further classified into Bridged and Bridgeless configurations. Bridged topologies have lower number of components, simple design, higher conduction losses and lower efficiencies for lower power levels; whereas, bridgeless configurations have larger number of components, lower number of components conducting per half cycle, reduced conduction losses and improved efficiency of the converter. Buck, Boost, Buck-Boost, Cuk, SEPIC, Zeta, Luo, CSC, Landsman and Sheppard Taylor converter topologies can be either Isolated, Non-Isolated, Bridged or Bridgeless or the combination of any two configurations. IHQRR is another class of PFC converters which integrate two converter topologies for attaining improved power quality at the AC mains. They offer reduced switching losses, higher efficiency and performance similar to that of single-stage converters. IHQRR can be BIFRD or BIBRED; the former integrates a Boost PFC converter with a Flyback converter, and the later integrates a Boost PFC converter with a Buck converter. IHQRRs promise an inherent power factor correction, improved power quality at the AC mains and higher system efficiency. The two operational modes of PFC converters include Discontinuous conduction mode (DCM) and Continuous Conduction Mode (CCM). DCM operation of PFC converters is preferred for low-power applications; while, CCM operation of the converter is preferred for medium and high power applications. Finally, it can be inferred that, the choice of a particular topology of PFC converter relies upon its efficiency, size, weight, cost and application for which it is intended to be used. And, the choice of the operational mode of a PFC converter is typically a trade-off between the switching stresses and the cost.

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