Asynchronous Grid Interconnection using Brushless Doubly Fed Induction Machines: Assessment on Various Configurations

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Abstract— **Electric power systems are commonly interconnected for cost effiective robust delivery purposes. Transmission interconnection benefits from load diversity, variety of sources and fuel prices. In addition; nation-level grid interconnection offers increased reliability, reduction of power interruption and generation-cost minimization. Various techniques are applicable for grid interconnection like High Voltage Direct Current links (HVDC), Variable Frequency Transformer (VFT) and Doubly Fed Induction Machine (DFIM). The development in machine construction enhances their capability. Various DFIMs are currently available such as the brushless twin stator cascaded doubly fed induction machines (BTDFIM) and the single frame brushless doubly fed induction machine (BDFIM). This paper discusses the application of grid interconnection using various doubly fed induction machines illustrating machine construction, operation and limitations.**

Keywords-grid interconnection; HVDC; VFT; DFIG; DFIM; BDTFIG; BDFIM

I. INTRODUCTION

The main reason for why different power grids are interconnected is the reduction of the overall economic costs in addition to the increase of the robustness and security of utility. In addition nation-level grid interconnection offers increased reliability, reduction of power interruption and generation cost minimization. Hence , for two grid systems interconnection, a robust and cost-effective connection is unavoidable.

Different topologies for grid interconnection have been proposed for linking two independent grids such as High Voltage Direct Current (HVDC) links, Variable Frequency Transformers (VFTs) and also Doubly Fed Induction Generators (DFIGs).

HVDC technology provides electricity transmission over long distances by means of overhead transmission lines or submarine cables. When compared to the traditional AC transmission, a DC transmission reduces transmission losses and investment costs. However the losses and the required capital cost for the terminals are higher for a dc system [1-2].

The control of dc power flow is robust. With proper control algorithm, the dc link can improve the system stability. A dc link is commonly utilized to connect two asynchronous power systems. This can be done with a "back-to-back" station, without a transmission line. The DC transmission has some features which are lacking in an AC transmission. Among those features:

- Power being transmitted is fully controlled
- Fault current limitation in DC lines is rapid

However, one of the major disadvantages of HVDC transmission is the high cost required to construct the converter stations, AC/DC and DC/AC conversion units. [2-4]

Recently an alternative technology for power flow control by means of the VFT (Variable Frequency Transformers) has imerged. [5-7].

A VFT can be considered as a controllable, bidirectional device able to interconnect AC grids comparable to a back-to-back HVDC system [8, 14]. The construction of the VFT is similar to that of the rotary transformer with three-phase windings on both rotor and stator. The current conduction between the three-phase rotor winding and its stationary bus-duct is the responsibilty of a three phase collector system of the VFT [9, 10]. The two independent grids ,where the power flow between them is to be controlled, are connected to VFT stator and rotor. Electrical power is exchanged between the two networks by the magnetic coupling through the air gap. The magnitude and the direction of power flow through the VFT is controlled by means of a drive motor and a variable speed drive system used to apply a torque to the rotor of the transformer thus adjusting the rotor position with respect to the stator which consequently controls the power flow. [11-13].

VFT is similar in construction to the doubly fed induction generator [15]. Hence it can be used as an alternative for grid interconnection. However the doubly fed induction machine (DFIM) has the famous disadvantage of the presence of slip rings which require increased maintenance costs and lead to reduced life time [16].

In order to overcome the drawbacks of the DFIG, brushless doubly fed induction machines (BDFIM) came into action. The absence of the slip rings and brushes reduces the losses and maintenance requirements [17, 18].

BDFIMs have different configurations including:

- *Brushless twin stator cascaded doubly fed induction generator*
- *Brushless doubly fed induction generator with nested loop rotor*
- *Brushless doubly fed induction generator with reluctance rotor*

In this paper, the utilization of BDFIMs for interconnecting two asynchronous grids is proposed as an alternative to HVDC and VFT. The proposed technique advantages and performance compared to HVDC and VFT are illustrated.

The presented paper is organized as follows: The HVDC transmission is discussed in Section II. The VFT utilization for grid interconnection is comprehensively addressed in Section III. The use of the Doubly Fed Induction Generator (DFIG) for the grid interconnection is presented in Section IV, while the proposed system of using the brushless doubly fed induction machines is illustrated in Section V. Finally, this study is concluded in Section VI.

II. High Voltage Direct Current (HVDC) Links

The HVDC links have different configurations and arrangements as shown in Fig.1 [1]. Due to the use of converters in the HVDC links it requires harmonic filtering, in addition to reactive power compensation [2]. Moreover, HVDC limitations arise when the ac power system on either side has low power rating compared to that of the HVDC. Further, as previously mentioned the need for conversion units at both sides adds more cost and foot-print burdens, due to the large number of high voltage switches and filter banks.

HVDC converters operations give rise to harmonic voltages on the dc side and harmonic currents on the ac side causing unacceptable voltage distortion, and overheating.

The converter stations absorb large amount of reactive power causing the current to lag the voltage hence consuming reactive power. Complex converter controls in addition to expensive DC breakers are commonly utilized to protect the system against dc short circuits since the current has no zero crossing [3].

The different HVDC arrangements include the following configurations:

A. Back-to-Back arrangement

Power grids required to be interconnected share neibouring teritories. Consequently, niether transmission line nor cable is necessary between the converters and the tie can be either monopolar or bipolar.

B. Two-terminal arrangement

For grids interconnection via dc transmission overhead lines/cables, two-terminal HVDC transmission is proposed.

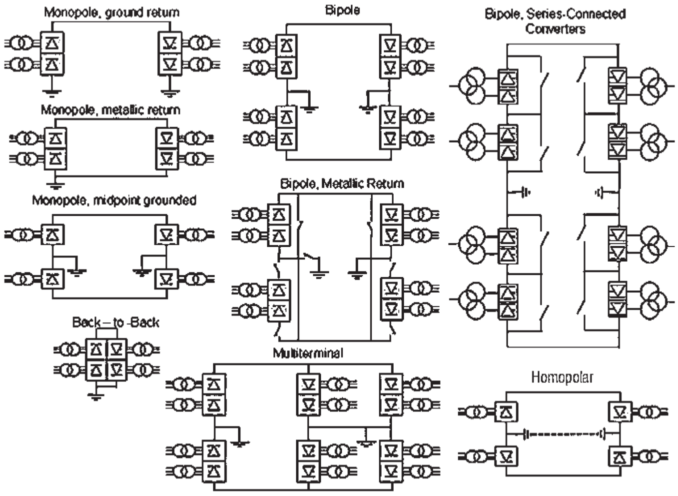


Figure.1 Various HVDC arrangements and configurations

C. Multi-terminal arrangement

For three or more HVDC substations; the HVDC transmission system is considered to be a multi-terminal arrangement. If the voltage level of the substations is the same and the substation capacity exceeds 10% of the total rectifier substation capacity , then the system is said to be a parallel multi-terminal. If one or more converter bridges are added in series in one or both poles, then the system is series multi-terminal. A combination of parallel and series converters forms a hybrid multi-terminal system.

III. Variable Frequency Transformer(VFT)

The Variable Frequency Transformer (VFT) is known for being a controllable, bidirectional transmission device.

It is a rotating phase-angle regulator with continuous controllability enabling power transfer from one grid to another up to 100MW. The construction of the VFT is similar to that of the rotary transformer with three-phase windings on both rotor and stator. The current conduction between the three-phase rotor winding and its stationary bus-duct is the responsibilty of a three phase collector system of the VFT as shown in Fig.2. VFT consists of two transformers, a switched capacitor bank and a DC motor as shown in Fig.3. The main principle is the rotor angle variation to change the power flow through the machine. The power flow is proportional to the torque applied to the shaft. In comparison to existing technologies, the VFT is capable to provide controlled transmission solutions, regardless of grid tie limitations [10]. The low grid interaction harmonics allows independent operation from other grid issues.

The VFT, in comparison to traditional HVDC technology, lacks high-voltage filters and hence offers a more compact substation design. A VFT substation has a smaller footprint; a complete 100MW VFT substation should occupy a space of about 30 m x 80 m.

However the VFT has some disadvantages since there are limitations on maximum power flow capability, besides it requires a reactive power compesation due to its increased reactive power consumption in addition to the requirement of step up/down transformers [5].

The simulations for VFT and HVDC systems both in steady state and dynamic mode proof their capabilty of accurate control of power flow.

However, the cosumption of reactive power in VFT systems compared to that of the back-to-back HVDC system is lower. Moreover the VFT offers a fast transient recovery and a better natural damping response. On the other hand, back-to-back HVDC converters have the advantage of offering a smooth and rapid recovery to the normal levels for the same fault comapred to the VFT system. [5].since both systems have their advantages and disadvantages, hence choosing one of them for a certain application relies to a great extent on economic issues. [14].

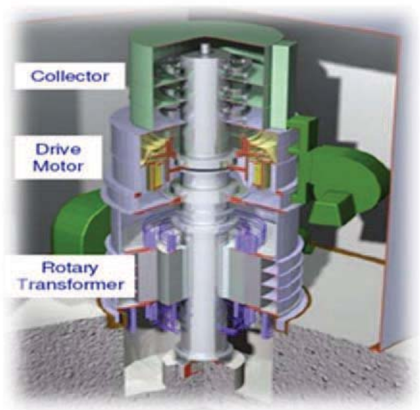


Figure.2. VFT structure [2]

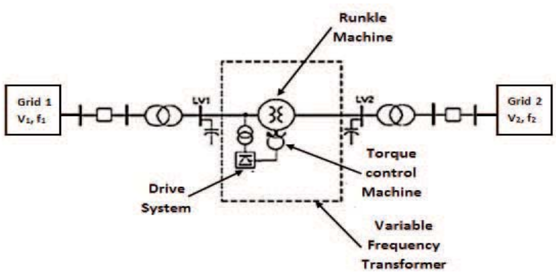


Figure.3 Two grids interconnection using VFT [7]

IV. DOUBLY FED INDUCTION GENERATOR (DFIG)

As previously mentioned, the VFT has three phase windings on both rotor and stator. The rotor angle is changed to alter the power flow through the machine which is in direct proportionality to the torque enforced on the shaft . Based on the above fact, VFT could be considered as DFIG where the machine torque controls the power flow from stator to rotor and vice versa [15].

Hence, the capability of using the DFIG for grid interconnection is discussed. When the induction machine is doubly fed, it operates at a synchronous speed that depends on the difference between both stator and rotor frequencies. The DFIG rotor rotates at a speed in diret proportionality to the difference between the two grids frequencies.

When two synchronized power systems are interconnected, the power flow is controlled at zero speed since the rotor is stall.

Similar to the VFT a DC motor is employed to command the power transfer of the DFIG. The arrangement is as shown in Fig.4.

The two grids to be interconnected are connected to the stator and rotor windings of the DFIG where power is to be transferred through slip-rings. In a doubly-fed induction machine, the rotor end is opened giving the ability to connect the rotor according to the system requirement.

If the applied voltages are synchronized, $f_s = f_r$, then the slip will be unity and the shaft speed falls to zero. At this condition, the machine acts as a stationary transformer preserving the option of changing the position of the rotor winding with respect to the stator winding . The impedance of the transformer can still be changed [16].

However if the applied voltage are asynchronous the slip will be non zero and the shaft rotates at a speed proportional to the difference between the stator frequency and rotor frequency. The doubly fed induction machine suggested for grid interconnection has the disadvantage of having slip rings and brushes which require regular maintenance. The slip rings lead to the reduction of the machine life time and high maintenance costs [17].

V. BRUSHLESS DOUBLY FED INDUCTION GENERATOR (BDFIG)

The brushless doubly fed induction generator has the advantange of overcoming the drawbacks of the doubly fed induction generator (DFIG) [21].

There are two configurations for BDFIG:

- Two machines configuration, known as the twin stator cascaded doubly fed induction generator.
- Single machine configuration, known as the brushless doubly fed induction machine.

Both of the above configurations can be used as an alternative for power transfer between two power systems.

A. Brushless twin stator cascaded doubly fed induction generator

From its name it is composed of two seperate wound rotor induction machines as shown in Fig.5. The merit of this type of machine over the conventional DFIG is the removal of the slip rings and the two rotors being electrically connected by connecting the terminals of the rotors [19]. According to fig.5. the two wound rotor induction machines are machine ‘A’and ‘machine B’. grid 1 (V_1, f_1) is connected to the stator of machine ‘A’ while grid 2 (V_2,f_2) is connected to the stator of machine ‘B’. the rotors of both machines are mechanically coupled and its mechanical motion is provided by means of a DC Motor while they are electrically

connected through the two rotors. Two rotating magnetic fields ,one of which is produced by the stator windings while the other is produced by the rotor windings, exist in the air gap of each machine.the magnetic field of the stator rotates at the synchronous speed (n_{sA} and n_{sB}) for machines "A" and "B" respectively. Since the two coupled rotors are rotated by means of an external DC Motor, hence the direction of rotation of the stator field can either be in the same or in opposite direction of rotation of the rotor.
In the twin stator cascaded doubly fed induction generator, there exists two current components in each rotor:

- One of them results from the induced emf generated due to the rotation of the stator magnetic field with respect to the rotor and it occurs in both rotors as a result of their electric connectivity
- The other current component is generated from the interaction with the magnetic field of the other rotor.

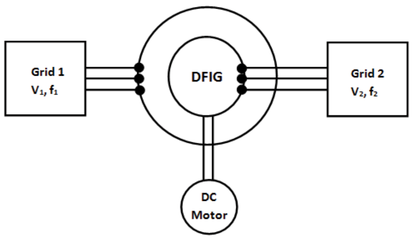


Figure.4 Two grids connected using DFIG

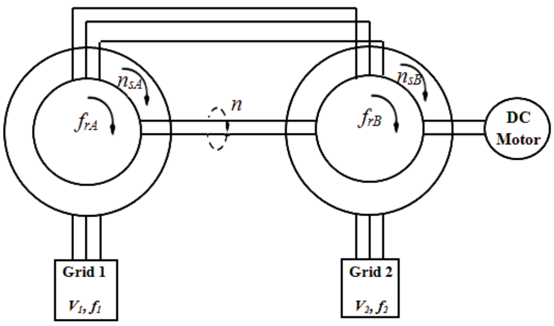


Figure.5 Twin Stator Cascaded Doubly Fed Induction Machines

Fig.6. shows the equivalent electrical circuit corresponding to the two coupled rotors.
The power flow through Grid 1.(e_A) to Grid 2. (e_B) by means of the current i_A and is computed from the equation below:

$$P=\frac{1}{T}\int_0^T e_B(t).\, i_A(t)dt \quad (1)$$

In order to obtain a value for average power both e_B(t) and i_A(t) have to be synchronized or else the average power will be zero. Hence it is targeted to fulfill the condition(s) at which e_B(t) and i_A(t) are synchronized (f_{rA}=f_{rB}).
The following terms will be introduced:
n_{sA} – the speed of the stator magnetic field of machine "A"
n_{sB} - the speed of the stator magnetic field of machine "B"
f_{rA} -the frequency of machine "A" rotor induced emf and magnetic field
f_{rB} - the frequency of machine "B" rotor induced voltage and magnetic field.
The electrical rotors connections account for the direction of rotation of this field and it permits various conditions, typically three cases can occur:

- *Case (1): The two stators' magnetic fields and the rotor speed n are in the same direction:*

$$f_{rA} = f_1\left[\frac{n_{sA}-n}{n_{sA}}\right] \quad (2)$$

$$f_{rB} = f_2\left[\frac{n_{sB}-n}{n_{sB}}\right] \quad (3)$$

The required condition for power flow as previuosly mentioned is:

$$f_{rA}=f_{rB}$$

From the above condition and substituting for the number of pole pairs of machines "A" and "B" , the rotor speed ***n*** at would be as follows:

$$n = 60\left[\frac{f_1-f_2}{P_A-P_B}\right] \quad (4)$$

Where, P_A and P_B are the number of pole pairs of machines "A" and "B" respectively. From equation (4), if the grids are synchronized (f_1=f_2), then the rotor speed is zero. The denominator of the speed *(P_A-P_B)* obligates the poles of the two machines to be unequal or else there will be no speed value at which the rotors' frequencies are equal and no power flow between the two grids takes place.

- *Case (2): The two stators' magnetic fields and the rotor speed n are in opposite direction*

$$f_{rA} = f_1\left[\frac{n_{sA}+n}{n_{sA}}\right] \quad (5)$$

$$f_{rB} = f_2\left[\frac{n_{sB}+n}{n_{sB}}\right] \quad (6)$$

The condition of power flow:

$$f_{rA}=f_{rB}$$

from the above condition and substituting for the number of pole pairs of machines "A" and "B" the required rotor speed ***n*** would be as follows:

$$n = 60\left[\frac{f_1-f_2}{P_A-P_B}\right] \quad (7)$$

Which is similar to the previous case.

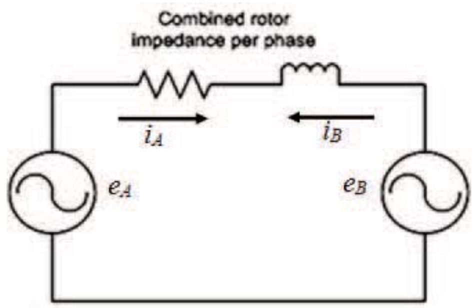


Figure.6 Electrical circuit of the combined typical rotors [19]

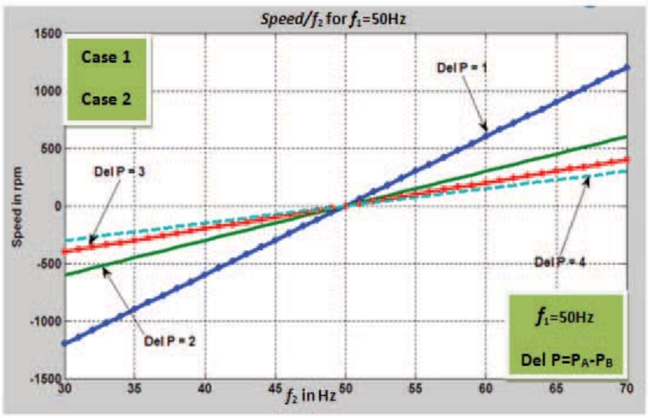


Figure 7. Variation of the required rotor speed with grid B frequency at different number of pole pairs (case (1,2)) [19]

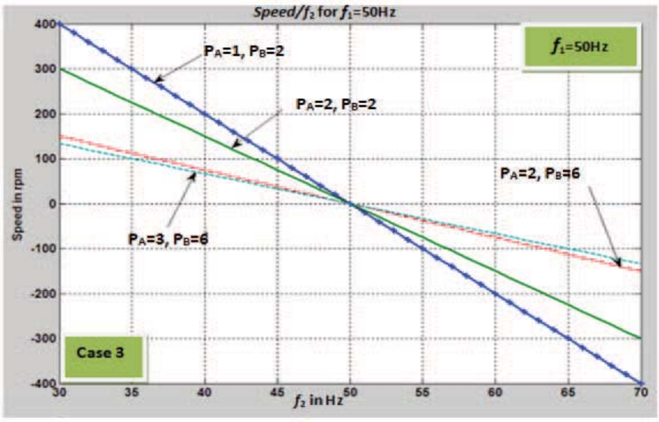


Figure 8. Variation of the required rotor speed with grid B frequency at different number of pole pairs (case(3))[19]

- *Case (3):The two stator magnetic fields rotate in opposite directions and one of them and rotor speed n are in the same direction.*

$$f_{rA} = f_1 \left[\frac{n_{sA}-n}{n_{sA}}\right] \tag{8}$$

$$f_{rB} = f_2 \left[\frac{n_{sB}+n}{n_{sB}}\right] \tag{9}$$

The condition required as previously mentioned is:

$$\boldsymbol{f_{rA}=f_{rB}.}$$

Similar as in the previous two cases:

$$n = 60\left[\frac{f_1-f_2}{P_A+P_B}\right] \tag{10}$$

In this case, by investigating the denominator $(P_A + P_B)$ there is a possibilty for the number of poles of the two machines to be equal. If the two interconnected power systems are synchronized (f_1=f_2), then the speed will be equal to zero and the system acts as a stationary transformer.

By investigating Fig.7 and Fig.8, it is shown that in the case when the two stator magnetic fields are rotating in the same or inverse direction of the rotor speed ,the speed range available is greater than when one of the stator magnetic fields is rotating in the same direction of the rotor speed.

B. Brushless Doubly Fed Induction Generator (BDFIG):

As previously mentioned, the brushless doubly fed induction generators are classified into two configurations one of them consists of two machines and the other configuration is one single machine with special rotors.

The Brushless Doubly-Fed Induction Machine (BDFM) versus the twin sator induction machine is a single machine having two three phase windings of different pole numbers on the stator and one rotor winding. In early designs, the stator winding comprised several coil groups shared by the two windings but recent BDFMs have two separate windings. The rotor windings of the BDFM are designed in a special way so as to couple the two stator fields.

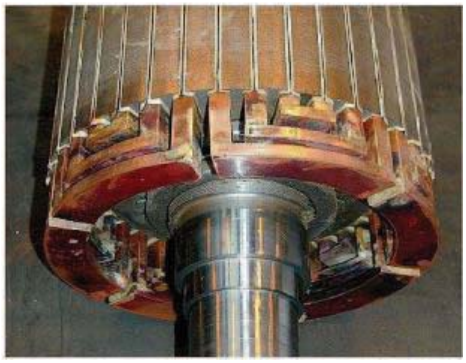


Figure 9. Nested loop rotor 4 pole – 8 pole (4/8) BDFM

B.1 Brushless doubly fed induction generator with nested loop rotor:

Most BDFMs are characterized by the nested loop rotor having a ($p_1 + p_2$) pole a. The nested loop rotor has ($p_1 + p_2$) nests each comprised of several concentric loops isolated or shorted at one end by a shared end-ring. Fig. 9 shows a nested loop rotor of a 4 pole – 8 pole (4/8) BDFM. Different configurations are also available using the conventional windings but maintaining the ($p_1 + p_2$) symmetry. [21-23].

B.2 Brushless doubly fed induction generator with reluctance rotor

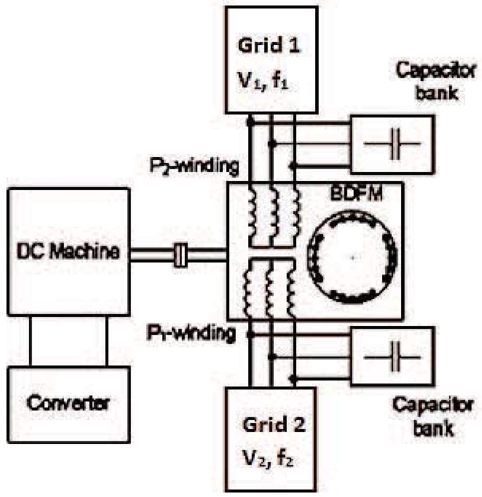
BDFMs give the possiblity of employing partially rated inverter and therefore offer reliable, maintenance-free operation at low cost, especially in large power variable speed applications with limited speed ranges. However, with a special cage rotor design, the machine has substantial rotor losses, poor efficiency and complicated control being difficult to implement.

The BDFM reluctance type, can overcome most of the BDFM deficiencies mentioned above while maintaining all its merits. It has a “cold” reluctance rotor thus having a higher efficiency and makes its modeling and control simple compared to the conventional BDFM.

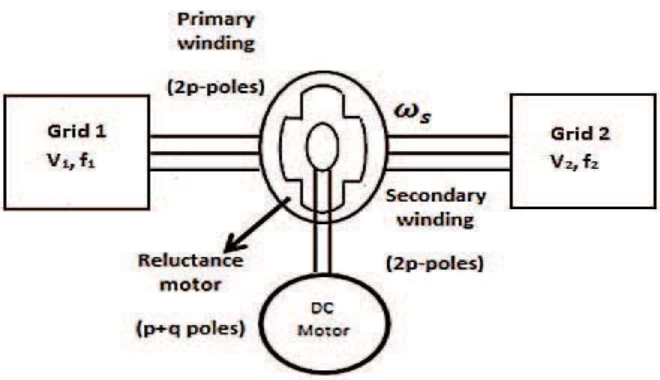
Another advantage of the BDFRM similar to all doubly-fed machines, is the ability to improve the line power factor being a useful property in weak networks but it may lead to the incraese of the inverter rating.

On comparing the BDFRM to the conventional BDFIM, the BDFRM have inherently decoupled control of active and reactive power components. The arrangement for grid interconnection using both the BDFM with nested loop rotor and reluctance rotor are implemented in Fig.10 (a) and (b) respectively.

The proposed system of using the BDFMs for the grid interconnection using the nested loop rotor and the reluctance rotor are an attractive alternatives to the conventional DFIG and also the BDFIM with squirrel cage rotor retaining the absence of the brushes and the presence of all windings in the stator with fixed output terminals, which is much suitable for bulk power transmission [27].



(a)



(b)

Figure. 10. Grid interconnection using:
(a) BDFM with nested loop rotor, (b) BDFM with reluctance rotor.

VI. CONCLUSION

The paper discusses various asynchronous grid interconnection techniques. HVDC links and VFTs have been investigated illustrating their limitations and requirements. New configurations for brushless doubly fed induction machines have been presented as an alternative for grid interconnection application. A preliminary comparison is presented featuring recent doubly fed machine configurations. A comparison between different configurations of the doubly fed induction machines is summarized in table (I)

TABLE I. COMPARISON BETWEEN DIFFERENT DOUBLY FED INDUCTION MACHINES FOR GRID INTERCONNECTION APPLICATIONS

	DFIM	BTDFIG	BDFM with nested loop rotor	BDFM with reluctance rotor
Number of machines	One machine	Two machines	One machine	One machine
Required driving system	DC motor	DC motor	DC motor	DC motor
Rotor construction complexity	simple	simple	complex	complex
Machine size	small	large	medium	medium
Maintenance	frequent	fequent	less	less
Decoupled control	required	required	required	required

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