POWER QUALITY GENERATED FROM DFIG WITH DIFFERENT TYPES OF ROTOR CONVERTERS

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ABSTRACT

In this paper the quality of power generated from wind energy conversion system employing a double fed induction generator (DFIG) is investigated. The DFIG performance is tested with 3 types of converters interfacing the rotor with the grid. These are: the six-step thyristor inverter with diode rectifier, six-step IGBT inverter with diode rectifier, and 3-level IGBT-PWM inverter with diode rectifier. The harmonics in current and voltage, power factor value, and the transient behavior in each system are investigated and compared. Comparison is done at sub-and super-synchronous DFIG operational speed. In the system with lowest power quality passive filters or LC filter are added and improvement in system performance is recorded. From this study the optimum system from point of view of cost and control complexity is concluded.

INTRODUCTION

In the last five years, a new technology has been developed in the wind power market introducing variable-speed working conditions depending on the wind speed in order to optimize the energy captured from the wind. The advantages of variable-speed wind turbines (VSWT) are that their annual energy capture is about 5% greater than the fixed-speed technology, and that the active and reactive powers generated can be easily controlled. As a disadvantage, VSWT need a power converter that increases the system cost. However, if double fed induction generator (DFIG) is used with VSWT, the overall cost of the power electronics is reduced because the rating of the converters interfacing the rotor with the grid, was proven to be only 10% of the DFIG rating [1].

When the wind speed changes, the rotor speed will change, and hence the rotor injection frequency should also be adjusted. A key requirement of a DFIG is to have its three-phase rotor circuit injected with a voltage at a controllable frequency and controllable magnitude. This three-phase ac voltage can be synthesized using various switching techniques, including six-step switching [2], pulsewidth modulation (PWM) [3], and space vector PWM [4].

In this paper the performance of the DFIG with three inverter techniques feeding the rotor circuit is investigated. These are the six-step switching thyristor inverter; the six-step switching inverter with passive filter, the six-step switching IGBT inverter, and the 12- pulse IGBT PWM inverter**.** The DFIG generation systems for each of the 3 types of converters is modeled and simulated giving the active and reactive power, the power factor, the stator voltage and current harmonics, and the systems' transient behavior. These results are obtained at both sub and super-synchronous speeds, since the double fed induction machine is known for its operation as a generator even at sub-synchronous speed at specific values of injected rotor voltage magnitude and phase angle **[5-7].** Results are compared and conclusion of optimum system trading off control complexity and cost is given.

A PID controller is tuned for each system to allow the DFIG to follow the wind speed in order to extract maximum power available from wind.

SUPER SYNCHRONOUS OPERATION OF DFIG

The performance of DFIG with the 3 types of inverters is investigated at speed of 190 rad/sec (slip = -0.11).

A. DFIG with six step switching thyristor inverter

While PWM technique is widely used for rotor injection [1], a six-step switching technique is another method to simplify the control circuit and reduce the switching losses. Six-step switching introduces $6n \pm 1$ harmonics in the voltages and the resultant output is a quasi-sine waveform. Unlike PWM, this does not need sine and triangular waves. It is easy to adjust the rotor injection frequency by simply varying a control voltage. The output line voltage of the inverter is a quasi-sine wave with levels 0, *VB*, and $-VB$ as shown in Fig. 2. For the quasi-sine waveforms of Fig. 1, triple-*n* harmonics (3, 6, 9, 15, . . .) are absent. The voltage waveform in phase A can be expressed in the mathematical form as [2]

$$v_{ra}(t) = V_S \sum_{k}^{\infty} \frac{1}{k} \sin(k\omega t) \quad (1)$$

Where k= 1, 5, 7, . *and* $V_S = (2/\pi)VB$

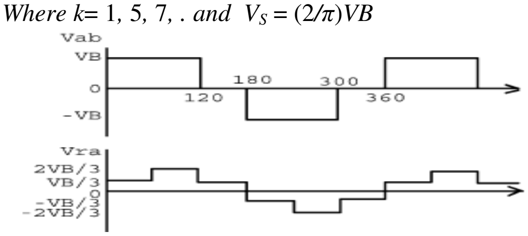

Fig. 1, 6-step inverter output voltage.

In a DFIG with quasi-sine rotor injection, the harmonics in stator currents and electromagnetic torque are dependent on the injected frequencies. The steady torques is developed by the reaction of harmonic air gap fluxes with harmonic rotor currents, of the same order. While the pulsating torque components, are produced by the reaction of harmonic rotor currents with harmonic rotating fluxes of different order. The steady torque can be expressed in current space vector as:

$$T_{e0} = 3\left(\frac{P}{2}\right) M I_m \sum_k \left[\overline{I}_{sk}, \overline{I}^{*}_{rk} \right] \qquad (2)$$

where k = 1, 5, 7, 9, 11, . . ., $I_k = (i_{qk} - j\, i_{dk})/\sqrt{2}$. The q–d variables are referred to the rotating reference frame with the same speed as the frequency of the stator harmonic component. Figures 2 & 3 show the output stator voltage & current with their harmonic content. In Fig. 3, the stator current reaches stability after 0.06 sec and the value of harmonic 1.18%.

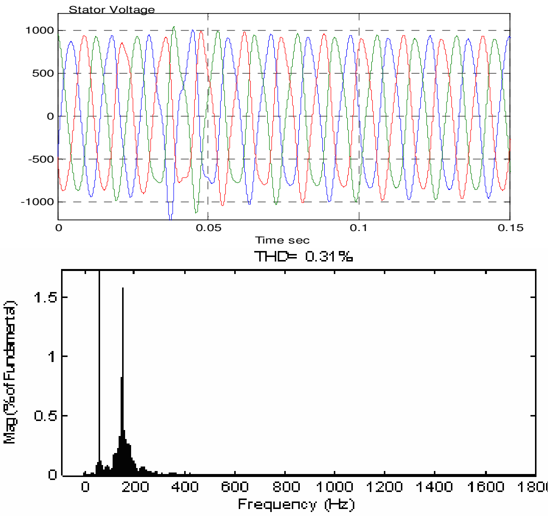

Fig 2 Stator Voltage and its harmonic content for six step switching thyristor inverter

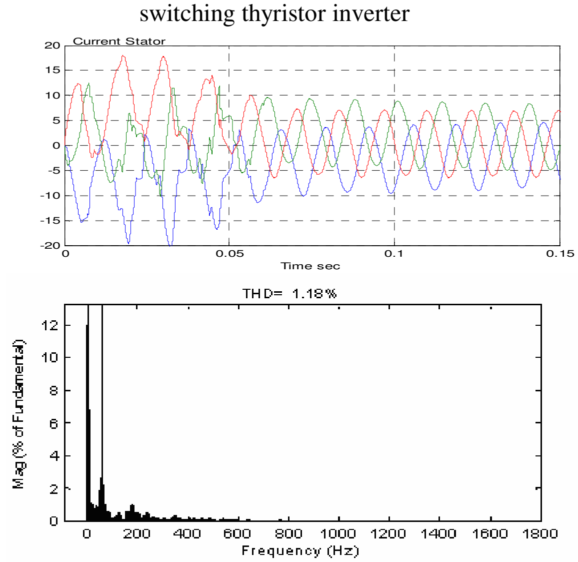

Fig 3, Stator current and its harmonic content for six step switching thyristor inverter

B. Six step switching thyristor inverter with LC filters

Due to the poor power quality obtained with this inverter, simulation is repeated with LC filter placed at stator side. Figs 4 & 5 show the output stator voltage & current with their harmonic content. It is clear that the value of harmonic increases compared to DFIG with six-step switching thyristor inverter. Hence multi-stage passive filter is suggested.

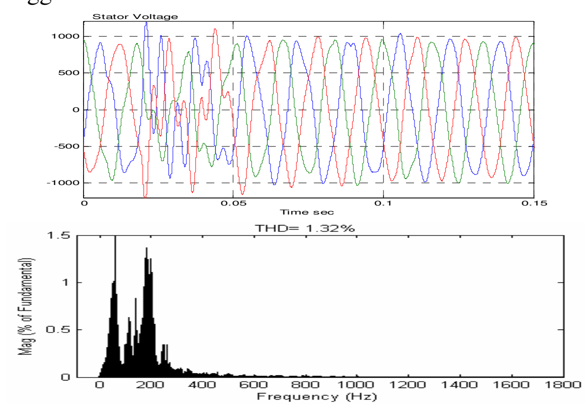

Fig 4, Stator V_S & harmonic content with LC filter.

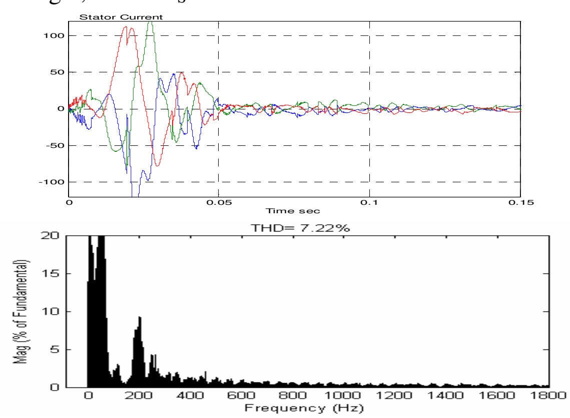

Fig 5, Stator current and harmonic content with LC filter

C. Six step switching thyristor inverter with passive filters

Due to the poor power quality obtained with this inverter, simulation is repeated with 3-phase passive filter shown in Fig. 6 placed at stator side. Figs 7 & 8 show the output stator voltage & current with their harmonic content. It is clear that the value of harmonic decreases compared to DFIG with six-step switching thyristor inverter.

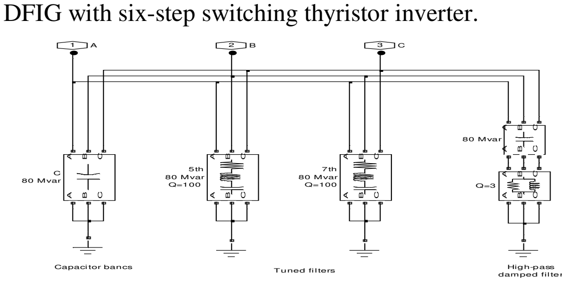

Fig. 6, 3-phase AC passive filter

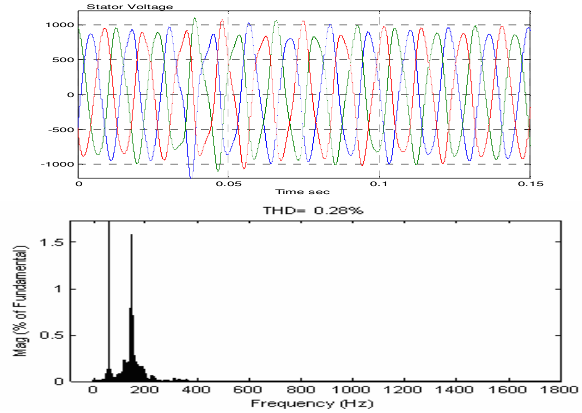

Fig 7, Stator V_S & harmonic content with passive filter

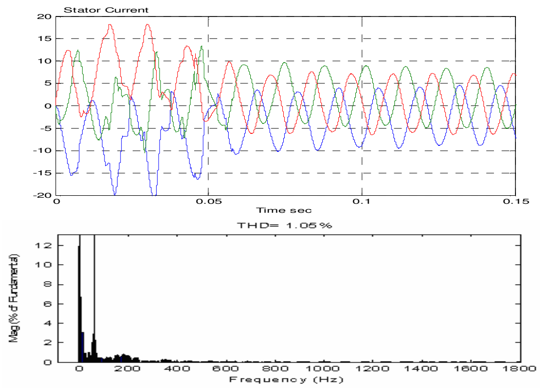

Fig 8, Stator current and harmonic content with passive filter

D. DFIG with six step switching IGBT inverter

Applying the 6-step switching technique to the inverter composed of 6 IGBT'S resulted in distorted stator voltage and current as shown by their harmonic contents in figs. 9 & 10. In these figures, it is clear that the harmonics of stator voltage and current increased than when using thyristors. Another drawback is the longer time taken to reach steady state.

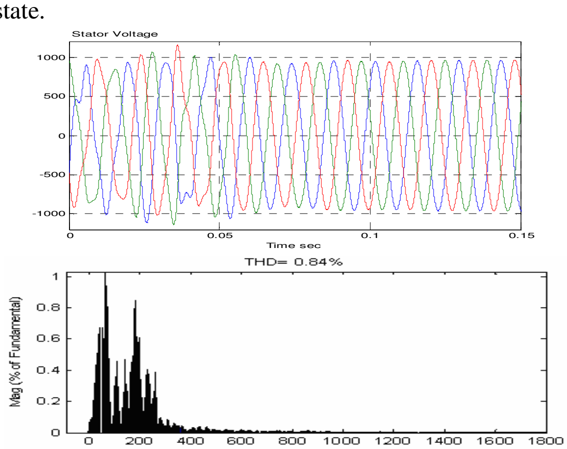

Fig 9 Stator Voltage and its harmonic content for six step switching IGBT inverter.

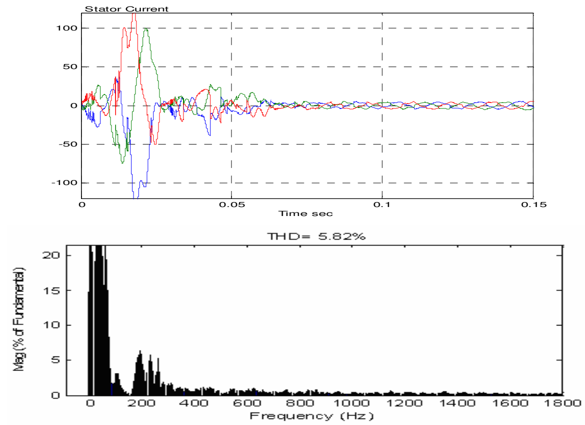

Fig 10, Stator current and its harmonic content for six step switching IGBT inverter.

E. DFIG with 3-level inverter

Applying 3 level inverter (12 IGBT) to the rotor circuit leads to better power quality than previous inverter types. This is obvious by the lower THD in stator voltage and currents shown in Figs. 11 & 12. In these figures, the THD in stator current decreased to 0.14 %, while it is only 0.1% in stator voltage. In these figures the time taken to reach steady state is 0.15 sec, which is much lower than previously considered inverters.

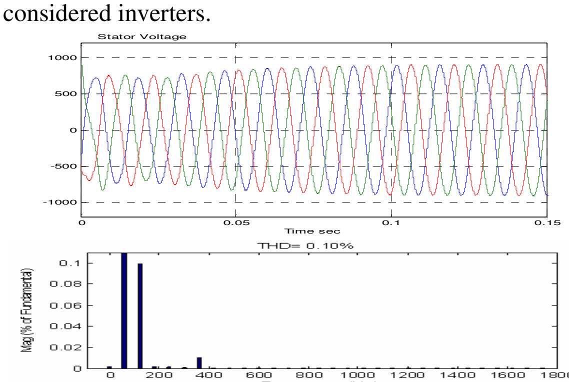

Fig 11, Stator voltage and its harmonic content for 3-level inverter

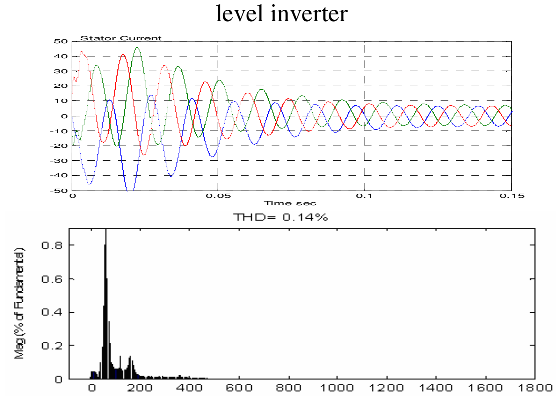

Fig. 12, Stator current and its harmonic content for 3-level inverter

Table 1: Comparing between systems at super-synchronous.speed

	6 step Thyristor			6 step IGBT	3 level Inverter
	only	LC filter	Passive filter		
Transient time	0.55	0.3	0.5	0.1	0.25
V harmonic	0.31%	1.32%	0.28%	0.84%	0.1%
I harmonic	1.18%	7.22%	1.05%	5.22%	0.14%
Overshot	5.5	7.1	5.5	20	12

Discussion of Results at super-synchronous speed

From Table I it is clear that 3 level inverter led to lower voltage and current harmonics. However the time for transient settling is better for the 6-step IGBT inverter. Also the overshot is minimum in case of 6-step switching thyristor inverter, and maximum when using IGBT.

DFIG PERFORMANCE AT SUB-SYNCHRONOUS SPEED

The performance of DFIG with the 3 types of inverters is investigated at speed of 185 rad./sec (slip = 0.11).

A. DFIG with six step switching thyristor inverter

The harmonic content of stator voltage and stator current shown in Figs. 13 & 14 respectively reveals the lower harmonics when operating the DFIG at sub-synchronous speed. The THD of voltage decreased from 0.31% to 0.18%, while THD of current decreased from 1.18% to 0.64%. This is roughly a 45% decrease in harmonics

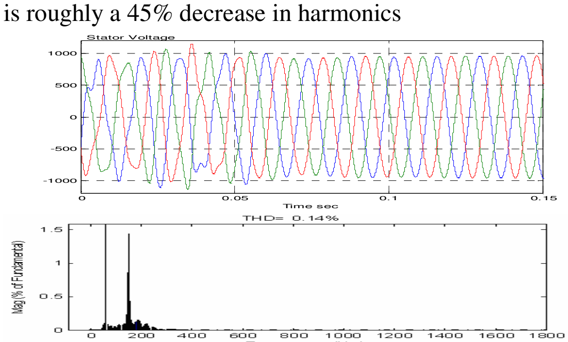

Fig. 13, Stator Voltage and its harmonic content for six step switching thyristor inverter

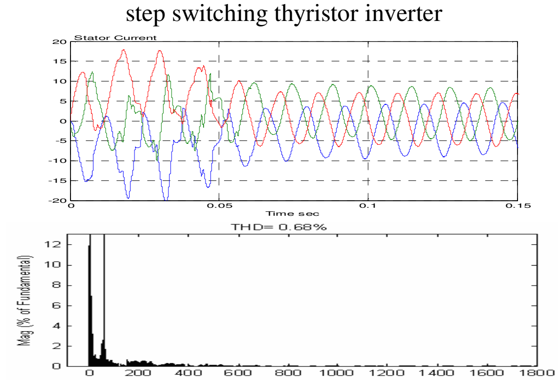

Fig. 14, Stator current and its harmonic content for six step switching thyristor inverter

B. DFIG with six step switching IGBT inverter

The harmonic content of stator voltage and stator current shown in Figs. 15 & 16 respectively reveals the lower harmonics when operating the DFIG at sub-synchronous speed. The THD of voltage decreased from 0.84% to 0.42%, while THD of current decreased from 5.82% to 3.42%. This is roughly a 50% decrease in harmonics

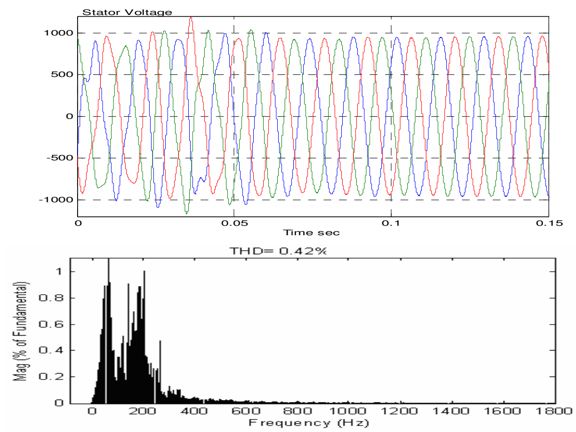

Fig. 15, Stator Voltage and its harmonic content for six step switching IGBT inverter

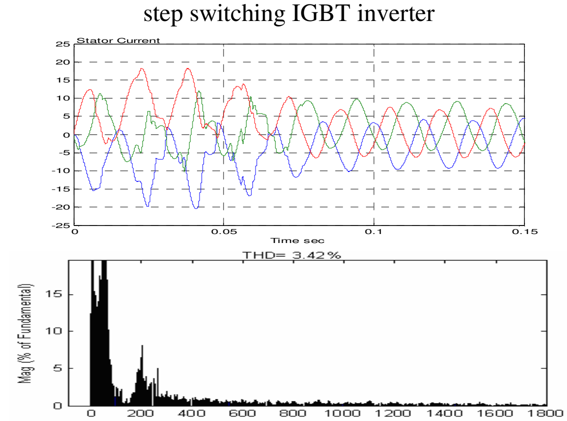

Fig. 16, Stator current and its harmonic content for six step switching IGBT inverter

C. DFIG with 3-level inverter

The harmonic content of stator voltage shown in Figs. 17 reveals again the lower harmonics when operating the DFIG at sub-synchronous speed. The THD of voltage decreased from 0.14% to 0.07%, which is a 50% decrease in harmonics contents. However the harmonic content of stator current shown in Figs. 18 increased.

Table 2: Comparing between systems at sub-synchronous.speed.

	6 step Thyristor	6 step IGBT	3 level Inverter
Transient time	0.8	0.1	0.07
V harmonic	0.14%	0.42%	0.07%
I harmonic	0.68%	3.42%	0.48%

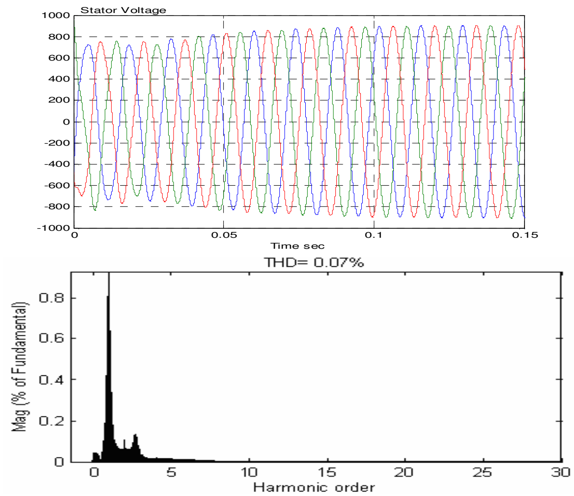

Fig. 17, Stator Voltage and its harmonic content for 3-level inverter

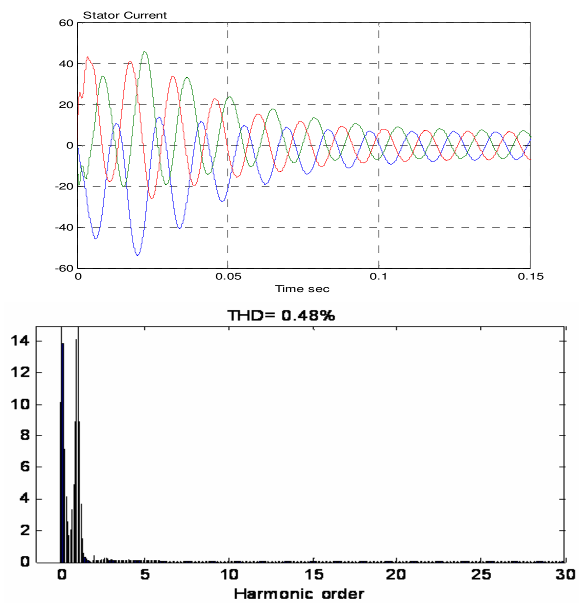

Fig. 28, Stator current and its harmonic content for 3-level inverter

From Table II it is clear that at sub- synchronous.speed., the 3 level inverter led to lower voltage and current harmonics. As well as minimum time for transient settling.

CONCLUSION

The performance of DFIG with 3 types of rotor inverters; 6- step thyristor inverter, six-step IGBT inverter, and 3-level PWM inverter is investigated. at sub-and super-synchronous speeds. The voltage harmonics, current harmonics, system power factor, active power, reactive power, and transient time for these cases are compared. Results revealed the better quality of power generated at sub-synchronous operational speed, where the harmonic contents decreased by roughly 45% than case of super-synchronous speed for 3 inverter types. In general, comparing performances showed that the higher harmonic contents occur with the six-step IGBT inverter, which is due to low switching frequency in the rotor circuit. Applying an LC filter to the 6-step thyristor inverter did not improve its performance. However, applying a 3 phase filter to the 6-step thyristor inverter decreased voltage and current THD by only 10%. The lower harmonics contents took place with the 3-level IGBT-PWM inverter while transient time was not minimum in case of super-synchronous operation.

The power factor is approximately the same for all cases. The oscillation damping time for voltage, current, and power is minimum for 3-level inverter (about 50% of transient time for other types). However the peak value of transient current and voltage are higher for 3-level inverter.

These results recommend operating the DFIG at sub-synchronous speeds, where lower wind speeds can be utilized, using the six-step thyristor inverter with passive filter. This leads to decrease cost and control complexity. Operation at sub-synchronous speed does not degrade the DFIG. On the contrary it is beneficial in sites with low wind speeds where the DFIG cannot be operated at super-synchronous speed.

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