Low Voltage Ride-Through Capability Enhancement of A DFIG Wind Turbine using A Dynamic Voltage Restorer with Adaptive Fuzzy PI Controller

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***Abstract*— This paper presents a low voltage rid-through (LVRT) capability enhancement strategy of a doubly-fed induction generator (DFIG) using a dynamic voltage restorer (DVR). The performance of the DVR depends on its controller. An Adaptive Fuzzy PI controller for the DVR is proposed to enhance the LVRT capability and fulfill the grid codes without disconnecting the turbine from the grid. Simulation results are presented for a 2 MW DFIG with a DVR system to validate the effectiveness of the proposed controltechnique.**

***Keywords*— Wind energy, doubly fed induction generator, dynamic voltage restorer, fault ride-through, fuzzy control.**

I. INTRODUCTION

The grid-connected DFIG must fulfill with the grid codes which include the LVRT guidelines, active / reactive power controls, frequency/voltage regulations, power quality, and system protection [1]. The disconnection of the wind turbine from the grid affects the power system stability and quality [2]. From grid codes, when a grid voltage dip occurs, the wind turbine must stay connected to the grid and continuously operates in the allowed duration as shown in Fig.1.

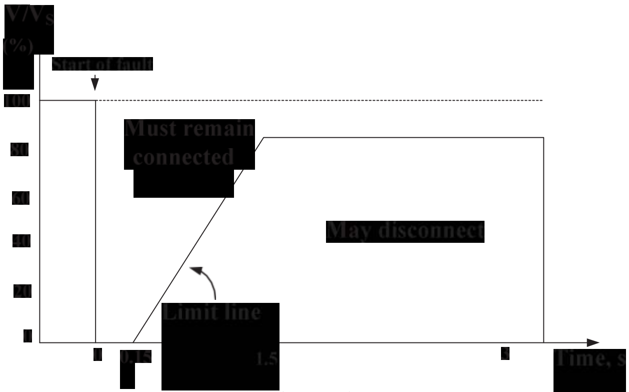


Fig. 1 Grid codes requirements.

The grid-connected DFIG wind turbine, shown in Fig. 2, provides variable-speed operation with separately controllable active and reactive power by using partial rating back-to-back power converters namely; rotor side converter (RSC) and grid side converter (GSC). However, it is sensitive to the faults of symmetrical and unsymmetrical grid voltage dips which lead to rotor overcurrent and DC-link overvoltage that affect the RSC and the rotor circuit [3],[4].

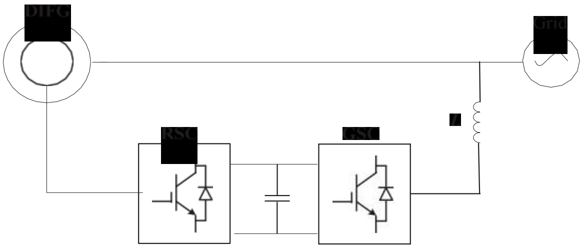


Fig.2. DFIG wind turbine configuration

To sort out this problem, crowbar circuit can be implemented in the DFIG rotor side [5]. However DFIG will absorb large amount of reactive power from grid which is not conducive for recovery during grid failure. Also it does not comply with the grid code requirements [6]. A static synchronous compensator (STATCOM) is presented in [7] to assist with the uninterrupted operation of a DFIG during LVRT. The DFIG becomes a conventional induction generator and starts to absorb reactive power during the voltage sage. The STATCOM is used to provide much reactive power which cannot be provided by theGSC.

The DVR can protect sensitive loads against grid disturbances such as voltage dip, sag, swell, and unbalance [8]. In [9]-[11], the DVR is presented to isolate the DFIG wind turbine from the grid during voltage dip as it is connected in series between the grid and the DFIG, whose voltage adds to the grid voltage in order to obtain the desired voltage [12]. However, it introduces a high cost solution. The type of controller of the DVR affects its performance. The PI controller offers simplicity and ease of implementation. However it is not adequate for systems with variable parameters and operating conditions due to its fixed gains [13]. Therefore, online tuning process should be performed. A lot of techniques have been presented to tune the PI gains [14]-[16].

In this paper, a DVR with adaptive fuzzy PI controller is proposed to improve LVRT capability of DFIG. The Simulation results show that DVR can enhance the DFIG wind turbine terminal voltage during grid voltage dips and enhance the LVRT capability.

II. DFIGCONTROL

The DFIG equivalent circuit in the synchronous rotating *d*-*q* reference frame is shown in Fig. 3. For stator flux-oriented control, the stator voltage, $v_{ds}$and v_{qs}, and rotor voltage, $v_{dr}$and v_{qr}, in the *d*-*q* referenceframe:

$$v_{dc} = R_c i_{dc} + \frac{d\beta_{dc}}{dt} - m_e h_{qs} \qquad (1)$$

$$v_{qc} = R_c i_{qc} + \frac{dh_{qc}}{dt} + m_e h_{dc}$$

$$v_{dr} = R_r i_{dr} + \frac{d\beta_{dr}}{dt} - (m_e - m_r) h_{qr} \qquad (2)$$

$$v_{qr} = R_r i_{qr} + \frac{dh_{qr}}{dt} + (m_e - m_r) h_{dr}$$

where,

R_s, R_r :Stator and rotor resistance.
L_{ls}, L_{lr} :Stator and rotor leakage inductance.
L_m: magnetizing inductance.
i_{ds},i_{qs}: The *d-q* stator currents.
i_{dr},i_{qr}: The *d-q* rotorcurrents.
c_e: The supply angular frequency.
c_r: The rotor angular frequency.
h_{dqs}: The *d-q* stator flux linkage;

$$h_{ds} = (L_{ls} + L_m)\, i_{ds} + L_m i_{dr}$$

$$h_{qs} = (L_{ls} + L_m)\, i_{qs} + L_m i_{qr}$$

h_{dqr}:*d-q* rotor fluxlinkage;

$$h_{dr} = L_m i_{ds} + (L_{lr} + L_m) i_{dr}$$

$$h_{qr} = L_m i_{qs} + (L_{lr} + L_m) i_{qr}$$

The vector control strategy decouples the active and reactive power.Thestatoractivepower,P_s,andconsequentlythe generator torque can be controlled by controlling the rotor *q*- axis current, i_{qr}, as

$$P_c = -\frac{3}{2}\frac{L_N}{L_c} v_{qc} i_{qr} \qquad (3)$$

While the stator reactive power, Q_s, can be controlled by controllingtherotor*d*-axiscurrent,i_{dr}as

$$Q_c = \frac{3L_N}{2L_c} v_{qcN}(i - i_{dr}) \qquad (4)$$

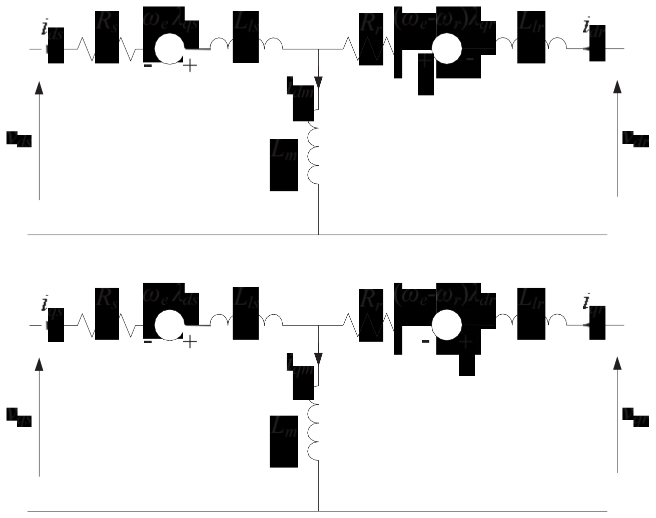


Fig. 3 DFIG equivalent circuit in *d-q* reference frame

The DFIG control system in the rotating *d-q* reference frame is shown in Fig. 4. The stator is connected directly to the grid and the rotor interfaced through the back-to-back GSCand RSC converters. The GSC is controlled to keep the dc-link voltage constant and to control the reactive power and inconsequence the power factor. The RSC controls independently the generator active and reactive power injected into the grid.

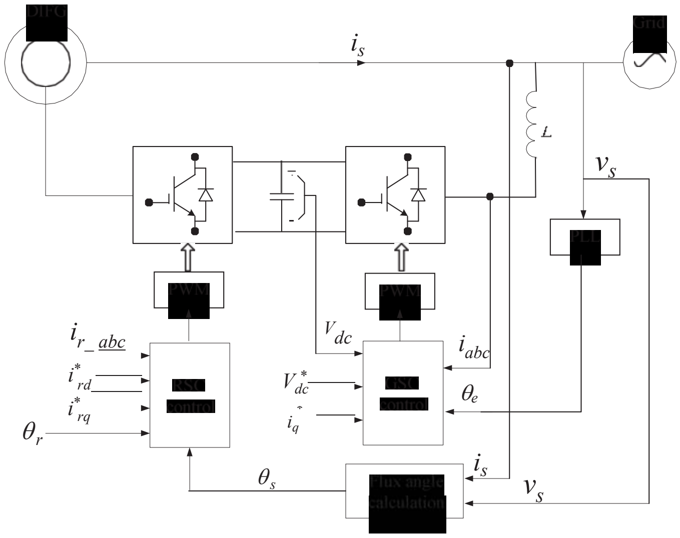


Fig. 4 DFIG control system

III. DYNAMIC VOLTAGE RESTORER(DVR)

The DVR is a three-phase voltage source converter connected in series with the power line via a coupling transformer to inject a compensation voltage. A low-pass *LC* filter is connected at the DVR output. The performance of the system with the DVR depends on the effectiveness of the used control technique [8].

The DVR can be used to enhance the LVRT of a DFIG in order to compensate the grid voltage dip. It is connected in series between the grid and the DFIG stator as shown in Fig. 5. During the grid voltage dip, the DVR injects voltages of controllable amplitude, phase angle and frequency in series and synchronized with the DIFG voltages via the series coupling transformer. This avoids disconnecting the wind turbine. The real power exchanged at the DVR output terminals is provided by the DVR input terminal by an external energy source or energy storage system[9].

The DVR control system is shown in Fig. 6. The measured three-phase grid voltage, v_g, is transformed into the *d-q* synchronous reference frame voltage quantities ($v_{gd}$and v_{gq}) rotating by the grid voltage angle *8* generated through a phase lock loop (PLL). The three-phase reference voltage is also transformed into the *d-q* reference frame, $v_{d_ref}$and v_{q_ref}. The reference and actual grid voltages are compared and the error signal acts on the PI controller. The controller output controls the switching of the DVR inverter in order to inject the proper compensation voltage via the series coupling transformer.

During normal operation, the DVR operates in a standby mode and injects nothing. This reduces the DVR losses.

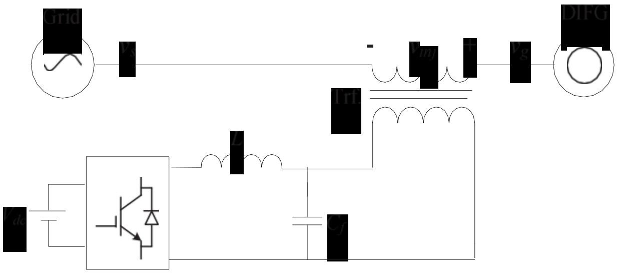


Fig.5. Grid connected DFIG wind turbine with a DVR

The rating of the DVR system depends on the depth of the grid voltage dip that should be compensated. The requirement of active power of the DVR is

$$P_{DVR} = \left(\frac{V1-V2}{V_1}\right) P_{Soad} \tag{5}$$

where V_1 is the nominal voltage and V_2 is the faulty line voltage. When the DVR compensates a voltage dip, the DFIG active power is partially fed into the grid and the DVR system. The active power flowing into the DVR charges its DC-link energy storage element. The DVR should have the same rating of the wind turbine power at full voltage dip. Hence, the DVR is implemented to enhance the LVRT capability at partial voltage dip and assist during full voltage dip [18].

A. DVR with PI Controller

The DVR with PI controller is shown in Fig. 6. The PI controller equation is

$$u(t) = K_p\, e(t) + K_i \int e(t) d(t) \tag{6}$$

where $u(t)$ is the control output in the d-q reference to be fed to the PWM generator. K_p and K_i are the proportional and integral gains, respectively. e is the error between the reference voltage and the injected voltage by the DVR. The PI controller offers simplicity and ease of implementation. However, the fixed gains during control operation affect the system performance especially the non–linear systems with variable operating conditions and parameters in addition to the transient response [19],[20].

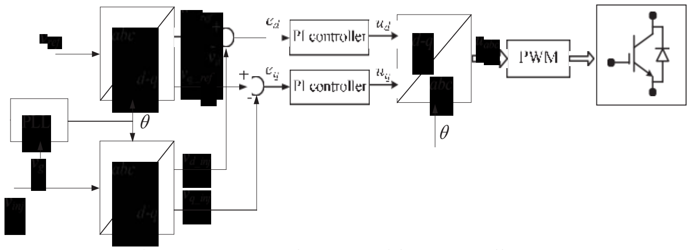


Fig. 6. DVR control system with PI controller

B. Adaptive Fuzzy PI Controller

The fuzzy logic controller (FLC) is a non-linear controller which does not require an accurate mathematical model of the system. The design of the FLC depends on the human expertise [21],[22].

In this paper, an adaptive fuzzy PI controller is used in the DVR control system to overcome the problems of the PI controller. The online tuning of the PI gains is shown in Fig. 7. The gain is adapted at any operating condition as a function of the error and its derivative. The output gain is considered as a fuzzy variable. The rule base is constructed by collection of If-Then rules. The values of the constants K_p and K_i are changed according to the error signal, e, and its derivative or rate of the error, Oe. The rule base is described for the parameter K_p in table 1 and for the parameter K_i in table 2 where the fuzzy variable are:

NB = Negative Big,
NM = Negative Medium,
NS = Negative Small,
Z = zero,
PS = positive Small,
PM = Positive Medium,
PB = PositiveBig

The rule base structure is implemented by repetitive simulation. The seven fuzzy sets are defined as shown in Fig.8. A complete fuzzy rule base consist of 49 rules can be obtained. For simplicity, assume that the fuzzy set of K_p and K_i are represented by the fuzzy set big 'B' and the fuzzy set small 'S' as shown in table 1 and table 2, respectively.

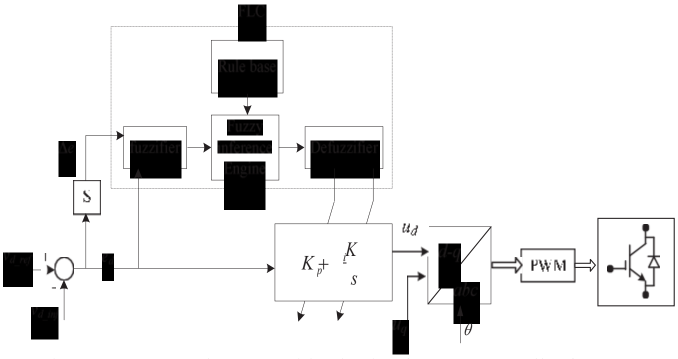
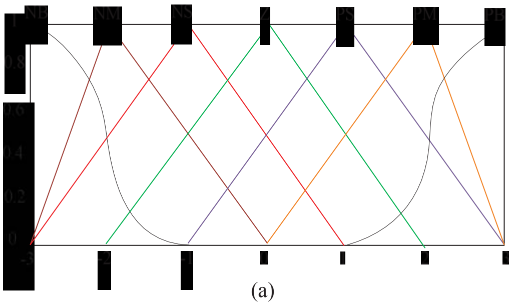
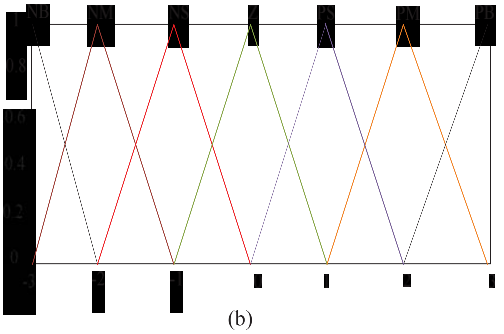


Fig. 7. DVR control system with adaptive fuzzy PI controller for



(a)



(b)

Fig.8 Membership function curves (a) inputs e and Oe(b) output $K_p$and K_i

TABLE 1. Fuzzy control rules forK_p

$^{e}/6e$	NB	NM	NS	Z	PS	PM	PB
NB	B	B	B	B	B	B	B
NM	S	B	B	B	B	B	S
NS	S	S	B	B	B	S	S
Z	S	S	S	B	S	S	S
PS	S	S	B	B	B	S	S
PM	S	B	B	B	B	B	S
PB	B	B	B	B	B	B	B

TABLE 2. Fuzzy control rules forK_i

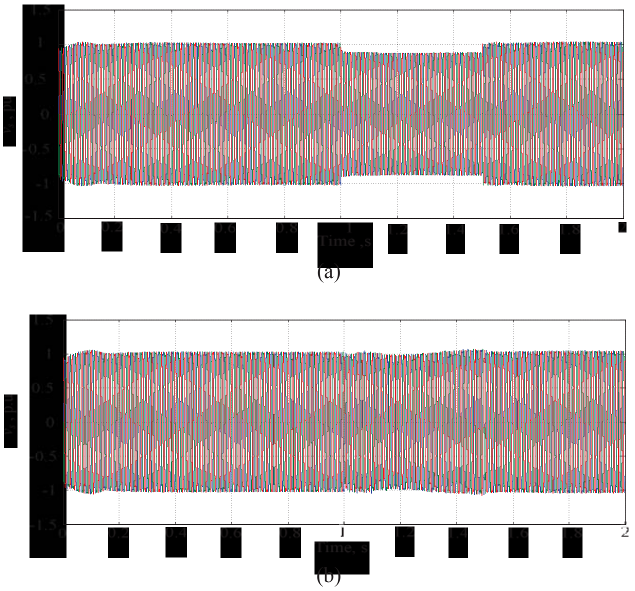
$^{e}/6e$	NB	NM	NS	Z	PS	PM	PB
NB	S	S	S	S	S	S	S
NM	B	B	S	S	S	B	B
NS	B	B	B	S	B	B	B
Z	B	B	B	B	B	B	B
PS	B	B	B	S	B	B	B
PM	B	B	S	S	S	B	B
PB	S	S	S	S	S	S	S

IV. SIMULATIONRESULTS

The performance of the DFIG wind turbine with and without the DVR under 10% balanced grid voltage dip from 1 to 1.5 s is investigated using a MATLAB/Simulink model. The parameters of the DFIG are listed in table 3. The results are shown in Fig.9 to Fig 14. The grid voltage dip is indicated in Fig. 9a. The DVR compensates the voltage dip resulting in DFIG stator voltage, v_s, of 1 pu during fault as shown in Fig. 9b. The amplitude of grid voltage, v_g, and the DIFG stator voltage, v_s, with DVR are shown in Fig. 10a and Fig 10b, respectively. The DFIG stator current, i_s, reaches 1.8 pu during fault as shown in Fig. 11a. This increase is almost mitigated when the DVR is activated as shown in FIG 11b. The DFIG rotor current, i_r, raises to 2 pu at the time instants of 1 s and 1.5 s as shown in Fig 12a. Due to the effect of the DVR, this current is limited to near 1 pu and increases onlyat 1.5 s to 1.2 pu as shown in Fig 12b. The DVR protects the DFIG converter from increasing of the DC-link voltage as shown in Fig.13. The rise of the DC-link voltage is due to the release of the active power in the DC-link during the fault. The active power with and without the DVR are shown in Fig. 14a and Fig. 14b, respectively. The active power is almost constant when the DVR is utilized.

CONCLUSION

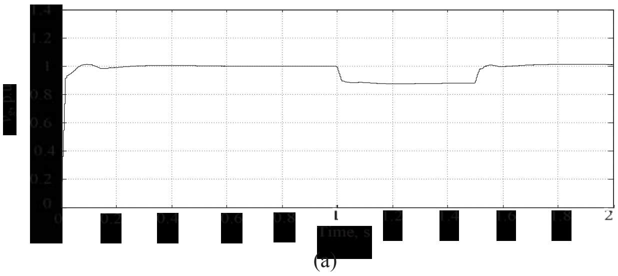
Enhancement of LVRT capability of DFIG wind turbines is important issue related to the utilization and connection of wind turbines to the electrical grid. During grid voltage dips, the system should comply with grid codes to ensure the normally operation of the wind turbine during the fault. The DVR is connected in series between the grid and the DFIG stator. It can be controlled to enhance the LVRT capability of a DFIG wind turbine. A DVR with Adaptive fuzzy PI controller has been used when grid voltage dips occur. A self tuning technique is mandatory especially for system with variable parameters and operating conditions. A wind turbine system of 2 MW is modeled using MATLAB / Simulink software. The Simulation results have demonstrates the capability of using DVR with the proposed controller to enhance the LVRT.



(a)

(b)

Fig.9 (a) Grid voltage at 90% voltage dip (b) DIFG stator voltage with DVR



(a)

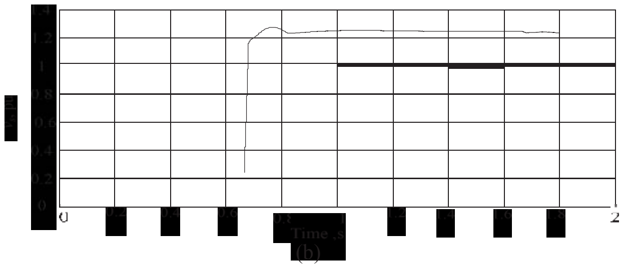


Fig.10 (a) Amplitude of grid voltage (b) DIFG stator voltage with DVR

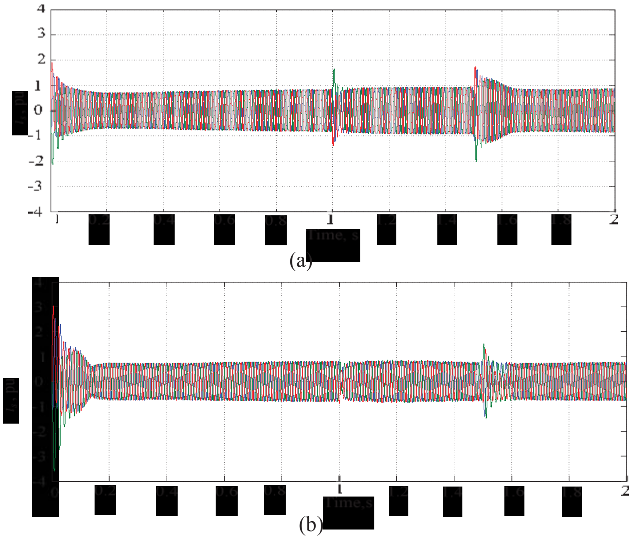


Fig. 11 (a) DFIG stator current without DVR and (b) with DVR

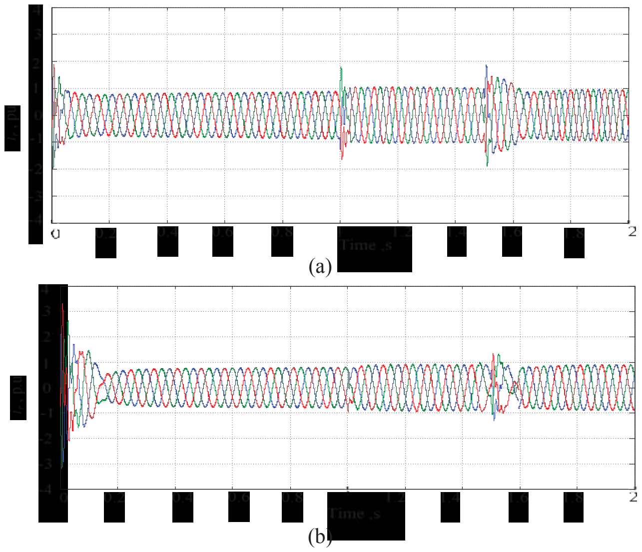
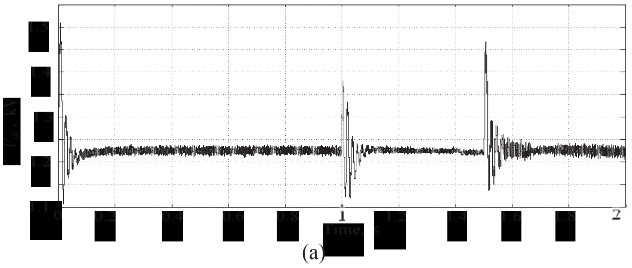


Fig 12 (a) DFIG rotor current without DVR and (b) with DVR



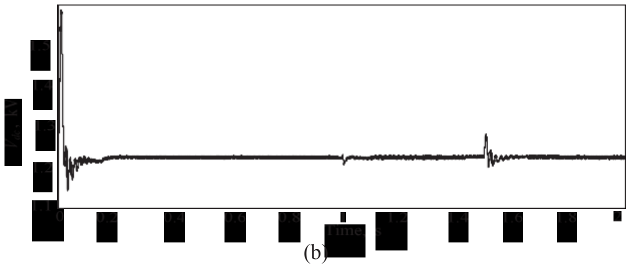


Fig .13 DC-link voltage (a) without DVR and (b) with DVR

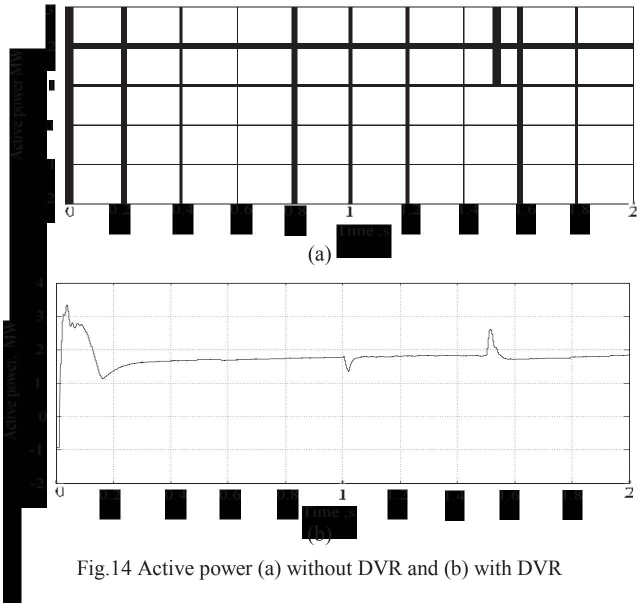


Fig.14 Active power (a) without DVR and (b) with DVR

TABLE 3: Parameters of DFIG

Parameters	Value
Rated power, MW	2.0
Rated line voltage, V	575
Stator resistance, pu	0.0006
Rotor resistance, pu	0.005
Stator leakage inductance, pu	0.171
Rotor leakage inductance, pu	0.156
Mutual inductance, pu	209
Number of poles	6
Grid frequency, Hz	50
Inertia constant	5.04
Nominal DC voltage, V	1200
maximum DC voltage, V	1900

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