COMPARISON OF "SEN" TRANSFORMER WITH DVR FOR LVRT SOLUTION OF DFIG WIND TURBINE

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Abstract: *Present scenario the electrical grid is being interconnected with different types of renewable energy sources. Among them the usage of doubly fed induction generators (DFIGs) in large wind farms has become quite common. The main difficulty of the DFIG is that it is very perceptive to grid side disturbances, particularly voltage dip/sags. This paper evaluates and compares the ability of a DFIG in a wind turbine to ride through a grid fault by injecting an adjustable series compensating voltage produced by dynamic voltage restorer (DVR) and proposed low voltage ride through (LVRT) solution 'Sen' Transformer (ST). The technology of transformers and tap changers is proven to be reliable and cost-effective when compared with the DVR emerging technology of multilevel convertor based DVR.*

Key words: *"Sen" Transformer (ST); DFIG; Low Voltage Ride through (LVRT); Multi level converter based DVR; Grid fault; Series voltage compensation*

Nomenclature

$\vec{i}$	Current space vector.
L_m	Magnetizing inductance.
L_{ls}, L_{lr}	Stator and rotor leakage inductance.
L_s, L_r	Stator and rotor self-inductance.
r	Superscript denoting rotor reference frame.
R_s, R_r	Stator and rotor resistance.
s, r	Subscript denoting stator and rotor.
$\vec{v}$	Voltage space vector.
$\vec{v}_{s-n}$	Nominal stator voltage vector.
$\vec{\psi}$	Flux space vector.
$\vec{\psi}_{s-n}$	Stator flux at normal condition.
$\omega_s, \omega_r, \omega_m$	Synchronous, slip, and rotor angular frequencies.
τ_s	Stator time constant.
σ	Leakage factor.
V_s	Nominal grid side voltage.
$V_{s'}$	Grid side voltage after compensation.
$V_{s's}$	Compensated voltage with ST.
A, B, C	Subscript denoting phase A, phase B and phase C.

1. Introduction

A power system has to provide high-quality of supply which means the voltage should be maintained at reasonable limits. All the load equipments are designed only to operate for a fixed value of voltage. In the recent years most of the electrical equipment is sensitive to short interruptions like doubly fed induction generators (DFIGs) [1]. So, there is a need to protect the equipment for these short duration faults. Voltage sags are considered as short duration faults. Some pieces of equipment trip when the rms voltage drops below 90% for longer than one or two cycles [2]. DFIGs are the most common type of advanced wind turbine generators due to their robustness, lower cost, simple structure and ability to adjust reactive power. One of the main drawbacks of using doubly fed induction generator is their defenselessness to grid side voltage sags or voltage dips and short circuits. This type of generator utilizes a power converter on the rotor to adjust the rotor currents in order to regulate the real and reactive power on the stator side. This converter is typically rated up to 30% of the generator power. When short circuit occurs on the grid side, the rotor currents rise and if the converter is not protected against these high currents, it will be spoiled. Recently, many researchers have focused on different techniques to overcome the ride-through issue of DFIG wind turbine. Multi level convertor(MLC) based dynamic voltage Restorer (DVR) is one of the devices that detects the sag or swell and connects a voltage source in series with the supply voltage in such a way that the system voltage is kept inside the established tolerance limits [3],[4],[5]. The DVR is a controlled voltage source that produces a voltage to be applied to the system with high efficiency, low harmonics content and fast response time. Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stress [1]; therefore electromagnetic compatibility (EMC) problems can be reduced. The "Sen" Transformer (ST) is also a promising, low cost voltage compensator that detects the sag or swells and connects a compensating unit in series with the supply voltage in such a way that the system voltage is kept inside the established tolerance limits [11].the ST uses reliable, cost-effective, and proven transformer and tap changer based technology.

Hence, the ST is adequate and economically attractive for ride-through applications. In this paper the MLC based DVR results will be compared to “Sen” Transformer (ST) as a voltage restorer.

2. Behavior of DFIG Throughout Grid Fault

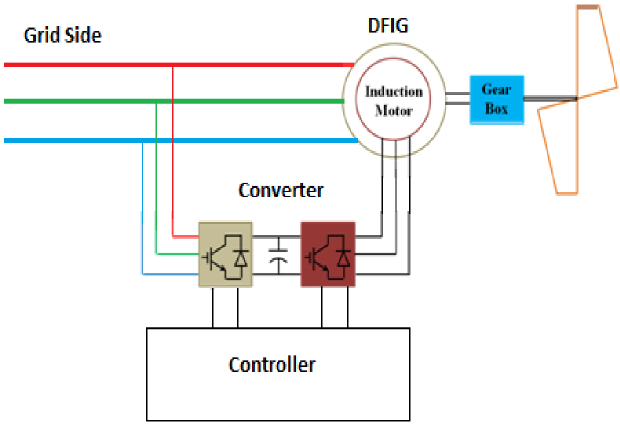


Fig.1 Configuration of DFIG wind turbine System.

So many researchers are discussed the modeling of DFIG wind turbines in various papers [6], [7]. Fig.1 shows the block diagram of a DFIG wind turbine system. The generator has a three-phase wound rotor supplied, via slip rings, from a four-quadrant, pulse width modulation (PWM) converter with voltage of controllable amplitude and frequency. A park model in the stationary stator- oriented reference frame developed for DFIG in [8], is used to analyze the effect of grid fault on the generator. In this model, the rotor variables are referred to the stator side for simplicity. Using motor convention, the stator and rotor voltages in *abc* frame can be expressed as

$$\overrightarrow{v_s} = R_s \overrightarrow{i_s} + \frac{d}{dt}\overrightarrow{\psi_s} \tag{1}$$

$$\overrightarrow{v_r} = R_r \overrightarrow{i_r} \frac{d}{dt}\overrightarrow{\psi_r} - j\omega_m \overrightarrow{\psi_r} \tag{2}$$

The stator and rotor fluxes are given by

$$\overrightarrow{\psi_s} = L_s \overrightarrow{i_s} + L_m \overrightarrow{i_r} \tag{3}$$

$$\overrightarrow{\psi_r} = L_r \overrightarrow{i_r} + L_m \overrightarrow{i_s} \tag{4}$$

Where $L_s = (L_{ls} + L_m)$ and $L_r = (L_{lr} + L_m)$

In Fig.2, the equivalent circuit corresponding to the aforementioned equations for the purpose of the rotor over- current analysis during the short circuit, the rotor voltage from converter point of view is the most important variable in the analysis [10]. This voltage is induced by the variation of the stator flux, which can be calculated by deriving i_s from (3) and substituting into (4).

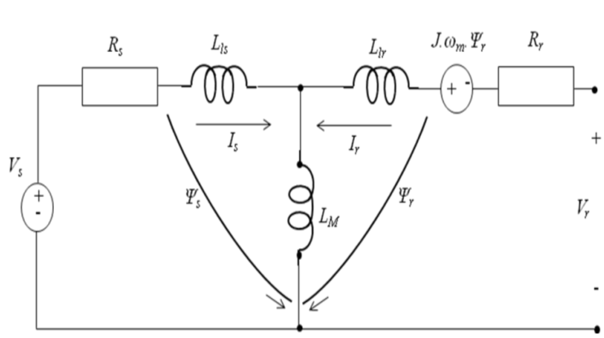


Fig. 2. DFIG-Equivalent circuit for short circuit analysis.

$$\vec{\psi}_r = \frac{Lm}{Ls}\vec{\psi}_s - \sigma L_r \cdot \vec{i}_r, \text{ here } \sigma = 1 - \frac{L_m^2}{L_s \cdot L_r} \tag{5}$$

Thus, the rotor voltage can be found by combing (2) and (5) as

$$\vec{v}_r = \vec{v}_s \frac{Lm}{Ls} s + (R_r + \sigma L_r (\frac{d}{dt} - j\omega_m))\vec{i}_r. \tag{6}$$

The rotor voltage given by (6) can be divided into two terms. The first term is the open circuit voltage ($\vec{v}_{ro}$) and it depends on the stator flux. The second term is smaller and it is caused by the voltage drop on both the rotor resistance Rr and the rotor transient inductance σLr . From (6), when there is no current in the rotor circuit, the rotor voltage due to the stator flux is ($\vec{v}_{ro}$).

$$\vec{v}_{ro} = \frac{Lm}{Ls}(\frac{d}{dt} - j\omega_m)\vec{\psi}_s. \tag{7}$$

Therefore under normal operation, the rotor voltage can be described as

$$\vec{v}_r = \vec{v}_s \frac{Lm}{Ls} s + (R_r + \sigma L_r (\frac{d}{dt} - j\omega_m))\vec{i}_r. \tag{8}$$

Where S is the slip ($S = \omega_r/\omega_s$, $\omega_r = \omega_s - \omega_m$)

The rotor resistance and the transient reactance are typically small. In addition, since the generator slip is limited to ±30%, the rotor current frequency is $fr < 18$ Hz [8]. As a result, the magnitude of V_{ri} in (8) is smaller than V_{ro} . The rotor voltage due to the stator flux can be written as

$$\vec{v}_{ro} = j\,\omega_r \frac{Lm}{L_s}\vec{\psi}_s = \frac{\omega_r}{\omega_s}\frac{Lm}{L_s} V_s e^{j\,\omega_s t} \quad (9)$$

The amplitude of the voltage $\vec{V}_{ro}$ can be described as a function of the amplitude of the stator voltage as follows.

$$V_{ro} = V_s \frac{Lm}{L_s} s \quad (10)$$

Throughout the normal operation, the rotor voltage V_{ro} depends on the magnitude of the stator voltage and the slip.But during short circuit on grid, based on reference [8], [1] the open circuit of rotor voltage is

$$V_{ro} = \frac{Lm}{L_s}\frac{\omega m}{\omega_s} V_s = \frac{Lm}{L_s}(1-S) V_s . \quad (11)$$

In equation (11) the rotor voltage is proportional to (1-S). Since the slip is in the range of –0.3 to 0.3 [10], it can be concluded that the amplitude of the voltage induced on the rotor winding during short circuit is closer to stator voltage. The ratio of rotor open-circuit voltage to rotor voltage caused by rotor impedance is larger in this case compared with steady state situation. It can even be higher if the machine operates at lower slips or at super synchronous speed. Full voltage dip/sag is not possible in real systems. Even though, this analysis gives the worst situation of DFIG. In any other situation, the voltages induced in the rotor are lower. Practically under short circuit condition partial voltage dip/sag will be occurring. At this situation the rotor voltage is

$$\vec{v}_{ro} = \left|\vec{v}_{s-n}\right| \frac{Lm}{L_s}(h.s.e^{j\,\omega_s t} - (1-h)(1-s)e^{-(t/\tau_s)}) . \quad (12)$$

Here, we define h as the ratio of the stator voltage before and after the sag as follows

$$h = \frac{\left|\vec{v}_s\right|}{\left|\vec{v}_{s-n}\right|} . \quad (13)$$

Equation (12) is the rotor voltage when there is no rotor current. However, during the normal operation, the rotor converter controls the rotor current in order to achieve the active and reactive reference power. The voltage in the rotor terminals that has to be generated by the converter is provided by

$$\vec{v}_{ro} = \left|\vec{v}_{s-n}\right| \frac{Lm}{L_s}(h.s.e^{j\,\omega_s t} - (1-h)(1-s)e^{-(t/\tau_s)})$$
$$+ (R_r + \sigma L_r(\frac{d}{dt} - j\,\omega_m))\vec{i}_r . \quad (14)$$

For a short circuit at turbine terminal, the abovementioned analysis is applied by setting h to 0.By substituting t=1 in equation (12), the following expression is achieved:

$$V_{ro} = \left|V_{s-n}\right| \frac{Lm}{L_s}(h.s - (1-h)(1-s)) \quad (15)$$

The two terms in (15) are different in nature. The first part is

$$\left|V_{s-n}\right| \frac{Lm}{L_s}.h.s = V_s . \frac{Lm}{L_s}.s \quad (16)$$

Therefore this voltage generated by the new grid voltage and its amplitude is small because it is proportional to the slip. And the second part of (15) is

$$\left|V_{s-n}\right| \frac{Lm}{L_s}(1-h)(1-s)$$
$$= \frac{Lm}{L_s}\left(\left|V_{s-n}\right| - \left|V_s\right|\right)(1-s) \quad (17)$$

Its amplitude is proportional to the depth of the voltage sag and to 1 – s. This voltage causes huge rise in the rotor current. If sag is compensated then h becomes equal to one in equation (15) then the second part of equation (15) will be removed. Sen Transformer (ST) and MLC based DVR used as voltage compensators. The objective in this paper is to compare the merits and demerits of the ST with the emerging technology of MLC based DVR and reveal the need for the new ST as cost-effective voltage compensators. Within the scope of this paper, an ST and a MLC-DVR are studied with both voltage restores connected to a simple wind turbine system.

3. Analysis of DFIG Wind Turbine during Grid Fault Without Compensation

The MATLAB/SIMULINK block diagram of the test setup is shown in Fig.3. Here, the DFIG is part of an offshore wind farm and that the voltage dip occurs nearer to the farm. The DFIG is connected to this grid through two transformers and a 30KM pi-model transmission line. The 415-V stator voltage of the DFIG is first transformed to 25KV; the rated voltage of the transmission line is 25KV. Afterwards, it is transformed to 120KV. Data of a 1-MW wind turbine with a DFIG have been used during the simulations. The machine parameters, as well as ST parameters, can be found in the Appendix. In fig. 4(a), the fault occurred at 0.6th second and cleared at 0.8th second at that period stator voltage falls down from 1p.u. to 0.3 p.u. almost 70% voltage will be decreased and in Fig.4(b), the rotor current increases 4 times during short circuit.

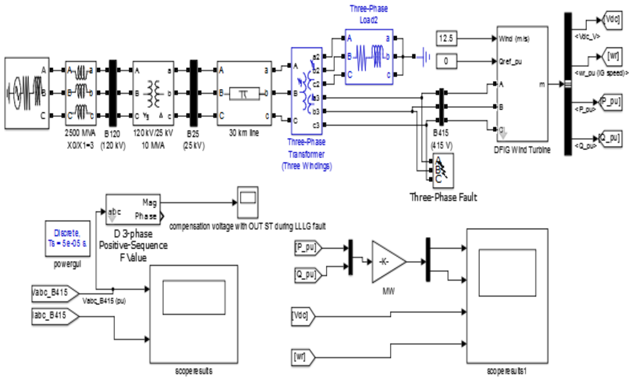
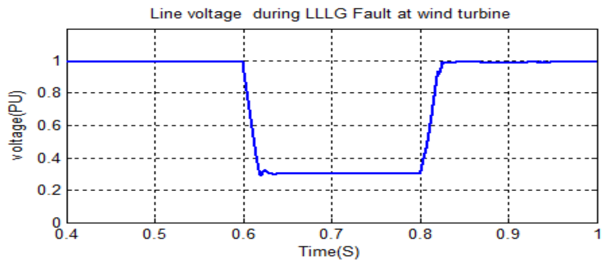
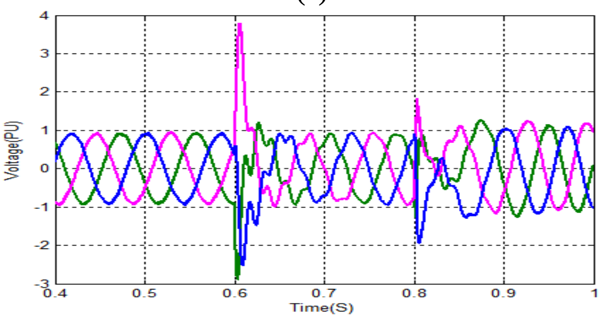


Fig.3 DFIG wind turbine during short circuit without compensation.



(a)



(b)

Fig.4. (a) DFIG stator voltage, (b) rotor current during grid faults without compensation.

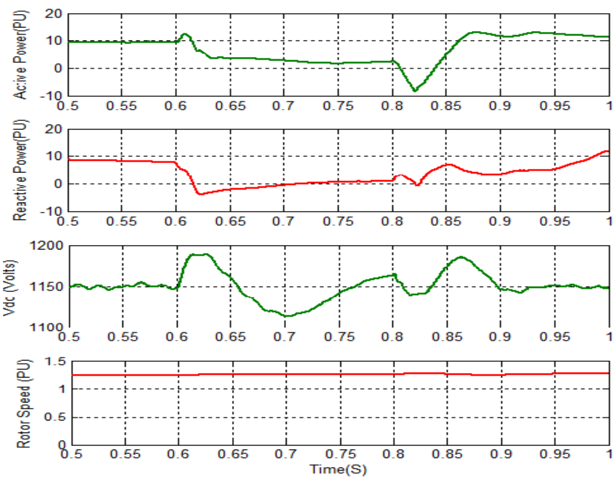


Fig 5. Simulation results for DFIG wind turbine during grid fault without compensation.

The figure.5 shows the deviation of active power, reactive power, dc voltage and rotor speed from normal state during fault condition without voltage compensation.

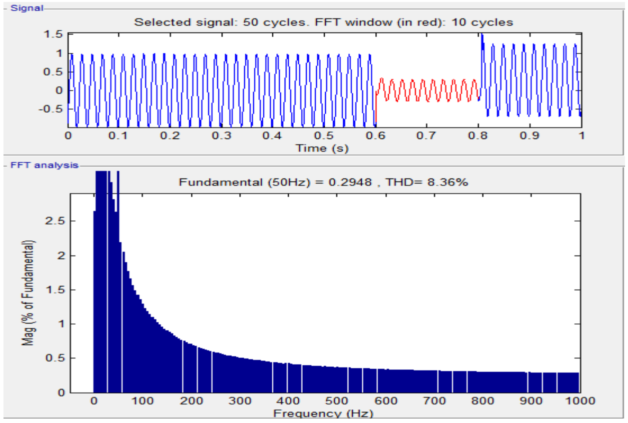


Fig.6. Total harmonic distortion during grid fault without compensation.

The above figure shows the total harmonic distortion of the power system during fault condition without using any compensation device.

4. Analysis of DFIG Wind Turbine during Grid Fault with MLC Based DVR

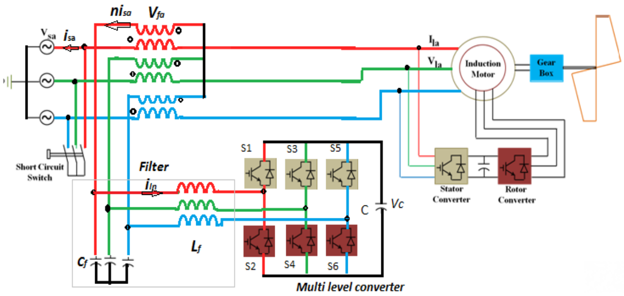


Fig. 7. Configuration of MLC based DVR for LVRT solution.

The block diagram of MLC based DVR for ride-through for DFIG wind turbine test setup is shown in Fig.7. A picture of the test setup in MATLAB/SIMULINK model is also shown in Fig.8. It is extension of Fig.3; it includes a five level voltage source inverter (VSI) operating at 20KHz switching frequency connected to the 3-phase 12 terminal series transformer (100 V : 100 V) for series voltage injection. This VSI is used to control the amplitude and the phase of the injected voltage. The phase voltages of the grid side is sensed and fed to a PLL implemented in the controller to generate the reference voltages. The actual grid voltage and reference voltages are compared to generate the reference voltage and gate commands for the series converter. The output voltage of the converter is applied to the stator side using three single-phase transformers. This configuration allows for independent compensation of phase voltages. Inductor L_f and capacitor C_f from a low-pass filter to remove the switching frequency harmonics from the output of the converter.

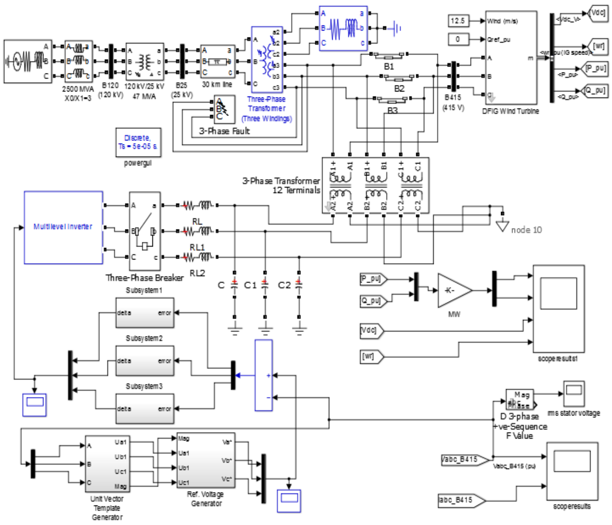
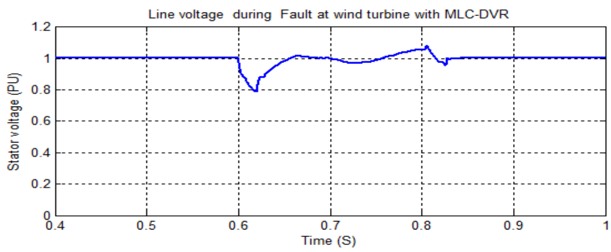
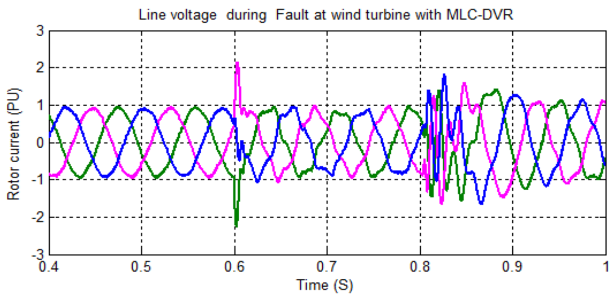


Fig.8. DFIG wind turbine during short circuit with MLC based DVR.

Fig.9. (a) shows the system behavior during the short circuit with MLC based DVR. It compensate the almost 95% voltage. Fig.9. (b) shows that the short circuit does not have any considerable impact on the rotor current. The rotor current stays within its normal value with small disturbance due to harmonic injection.



(a)



(b)

Fig.9. (a) DFIG stator voltage, (b) rotor current during grid faults with MLC-DVR.

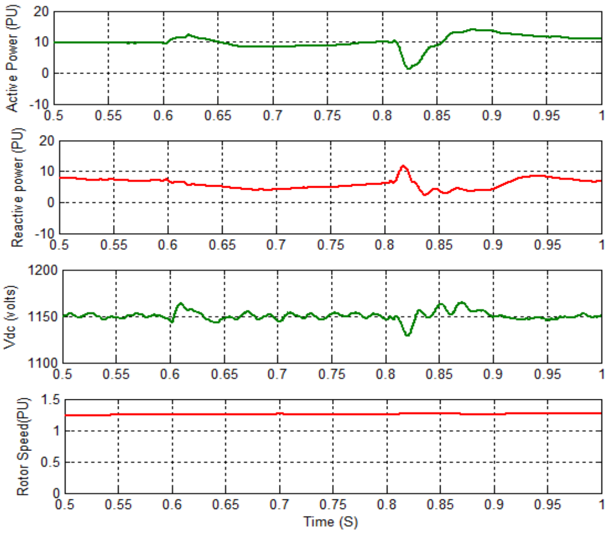


Fig 10. Simulation results for DFIG wind turbine during grid fault with MLC based DVR

The above figure shows no deviation is occurred in active power, reactive power, dc voltage and rotor speed from normal state during fault condition with MLC Based DVR.

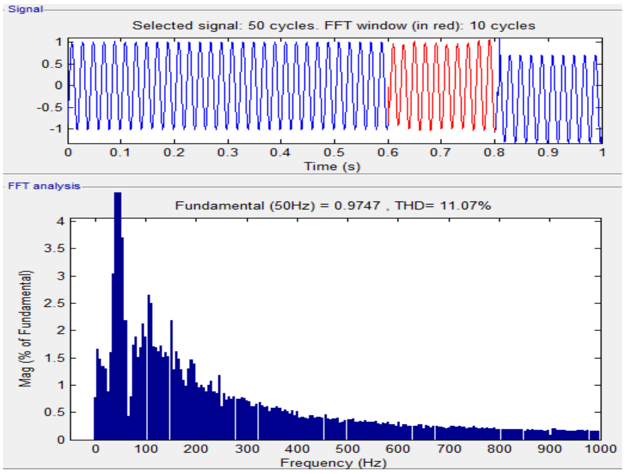


Fig.11. Total harmonic distortion during grid fault with MLC-DVR.

5. Analysis of DFIG Wind Turbine during Grid Fault with Sen Transformer

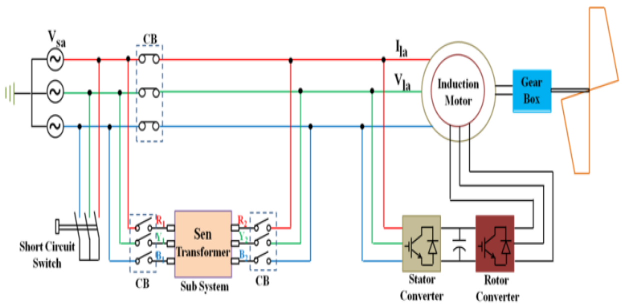


Fig.12. Configuration of the “Sen” Transformer for the proposed LVRT solution for DFIG wind turbine.

So many references have discussed the behavior of "Sen" Transformer (ST) as a power flow controller [9], [10]. Not only power flow controller ,it is also a low voltage ride through solution for a specified power system during grid faults [11].In this paper the ST is used as a voltage restorer during grid fault for DFIG wind turbine. The configuration of the "Sen" Transformer for ride- through test setup is shown in Fig.12. A picture of the test setup in MATLAB/SIMULINK model is also shown in Fig.13. It is extension of Fig.3; it includes a "Sen" Transformer (ST) sub system through bypass circuit breakers.

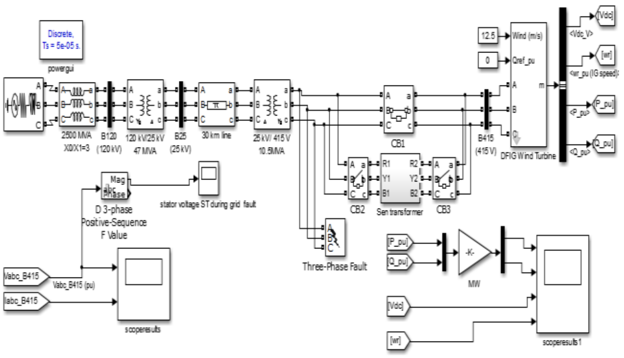


Fig.13. DFIG wind turbine during short circuit with "Sen" Transformer.

Fig.14 shows the schematic diagram of the "Sen" Transformer (ST). Schematic of ST comprises of two units primary is the exciter unit and the secondary is the compensating unit. The secondary is like a desirable on load tap changing transformer. It is a multi-winding transformer having each winding distributed on each phase. The compensating voltage unit consists of nine secondary windings, three windings from phase a, three from phase b and three from phase c. These secondary windings are interconnected to get entire 360^{O} of operation. This is the main advantage of ST as a power flow controller i.e. we can able to add the compensating voltage in series with the line from 0 degrees to 360 degrees

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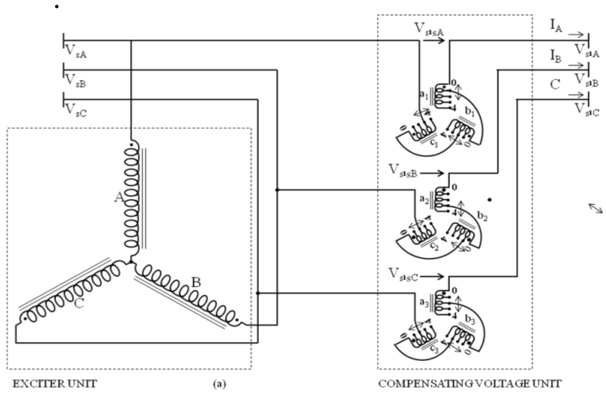


Fig.14: schimatic diagram of Sen Transformer

As shown in Fig.14 each phase consists of three secondary windings one from phase a, one from phase b, and other from phase c, in a three phase transmission system each phase is having a phase difference of 120 degrees with that of previous one. Fig. 15 shows the complete phasor diagram of ST, where a series voltage $V_{S'S}$, from ST added to the phase voltage V_s at an angle **β**(leading), to produce the resultant voltage $V_{s'}$.The angle **β** can be varied between 0^o and 360^o. Every tap of compensating unit connected with a triac, if there is any voltage sag/dip in the system the best combination of the taps

Selected by programmable logic controller and it injects necessary voltage for DFIG wind turbine for ride through applications.

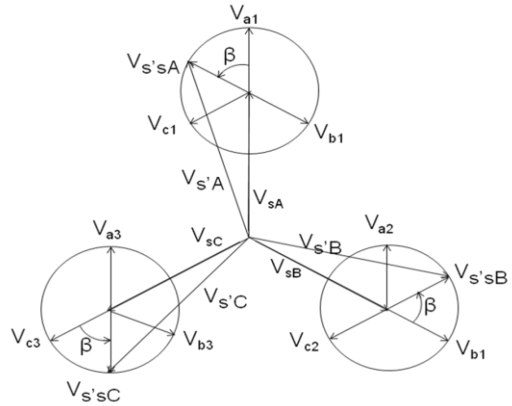
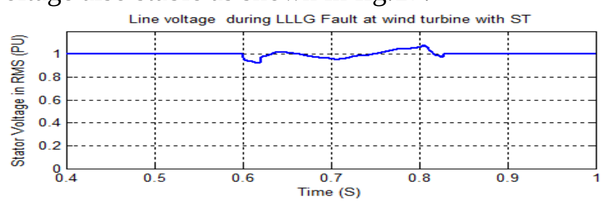
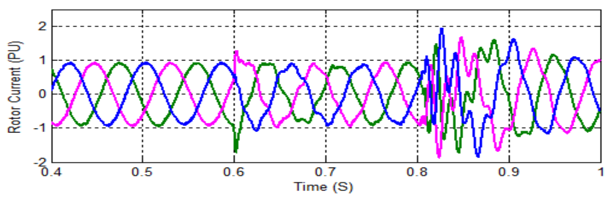


Fig.15: phaser diagram of Sen Transformer

In Fig.13, The ST is connected in series with wind form through bypass circuit breakers and it shows the short circuit fault arrangement. The dip is occurred from 0.6^{th} second to 0.8^{th} second. Fig.16 (a) shows the system behaviour during the short circuit with almost full voltage compensation on stator side. Therefore, the short circuit does not have any significant impact on the rotor current as shown in Fig. 16 (b) and dc link voltage also stable as shown in fig.17.



(a)



(b)

Fig.16. (a) DFIG stator voltage, (b) rotor current during grid faults with ST.

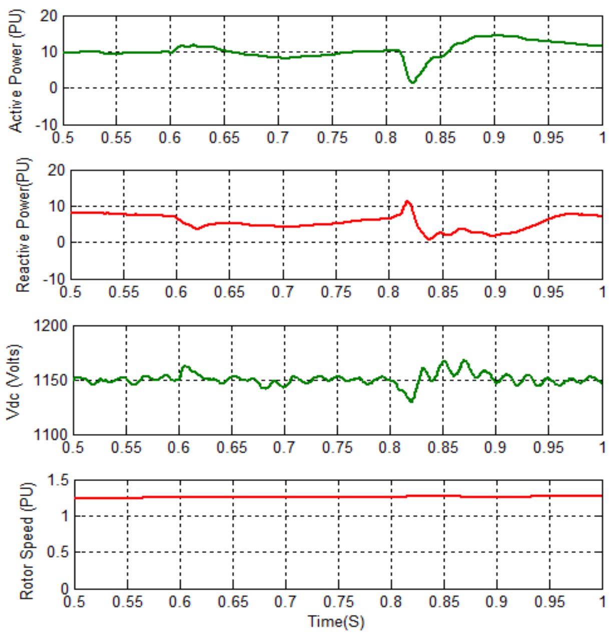


Fig.17: Simulation results for DFIG wind turbine during grid fault with ST.

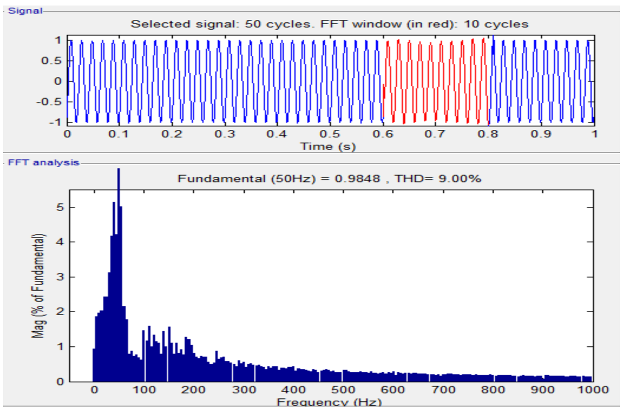


Fig 18: Total harmonic distortion during fault with ST.

6. Comparison between MLC DVR and ST

From simulation results Fig.4 (a), Fig. 9 (a) and fig.16 (a) we observed that ST mitigate the sags up to 98% and MLC-DVR mitigate the sags up to 92% but switching transients are more in MLC DVR compare to ST. from fig.6, 11, 18 in ST operation, the total harmonic distortion is less compared to DVR. The proposed ST does not have dc link and consequently there is no limitation about Compensation time and there is no harmonic production during the steady state operation. Switching losses are more in MLC DVR because of it has power electronic convertor. The technical performance of MLC-DVR and ST is shown in table-1.

Table 1

The technical performance of ST and MLC-DVR

SL. No	DFIG	Grid Voltage (PU) With normal condition	Grid Voltage (PU) during Fault condition	Rrotor side current (PU) during Fault condition	THD (%) at Grid during Fault condition
1	With out compensation	1	0.3	3.9	8.36
2	With MLC Based DVR	1	0.9	2	11.07
3	With ST	1	0.95	1.3	9

The MLC DVR is composed of voltage source converter with eight IGBTs with eight diodes in anti-parallel (in order to allow imposing zero-sequence components for compensating Single-phase faults). There is also a high cost dc capacitor.The proposed ST neither uses rectifier stage nor can dc capacitor and triacs be used as switching devices, resulting in a significant cost reduction. The switching occurs only when a change in the switching state is needed, increasing the efficiency and avoiding expensive heat sinks. The control system is very simple, eliminating the need of powerful computational platforms, causing a cost reduction and reliability increase. The comparative study is tabulated given below

Table-2

Comparison between MLC based DVR and an ST

S.No	**Parameter**	***MLC-DVR***	***ST***
1	Ability to compensate phase-angle displacement	NO	Yes
2	Cost	More	Very less
3	Number of components or complexity	More	Less
4	Adequate dynamic response for utility power flow regulation	Yes	Yes
5	Estimated losses at rated power	10%	1%
6	Reliability and high availability	Less	More
7	Compensating voltage steps depend on number of taps installed	No	Yes
8	compensation time	Limited	Unlimited

7. Conclusion

Till now ST was used as a static active and reactive power compensator, now a new voltage ride through solution by using ST is proposed to operate the DFIG wind turbine without losing its power electronic converters during grid faults. By using MATLAB/SIMULINK, a comparative analysis between the proposed and multi level converter based dynamic voltage restorers is done and simulation results are presented. At present most of the wind turbines are of variable type doubly fed Induction Generators (DFIG). As, these DFIG'S are the induction generators they will draw reactive power from the grid, so during the time of faults there is overburden on the grid. To, maintain the voltage profile in these times ST is used as a compensator in place of power electronic components. The expenses for the taps and the controller in the ST are only a fraction of the expenses of the power electronics and accessories in the MLC-DVR. Moreover, the DVR mitigate the sag with limited time only but the ST mitigates the sag with unlimited time and the efficiency of an ST is above 99% and that of MLC- DVR is the range of 92 to 97%. Therefore, the life time operating cost of MLC-DVR is significantly higher than that of an ST. At the present time, two major drawbacks of all voltage source converter- based controllers are their high installation and operating costs. In comparison to a MLC-DVR, a 5:1 reduction in equipment cost and 10:1 improvement in operational cost of an ST are expected.

Appendix

The DFIG and Sen Transformer parameters that have been used during the simulations are given below.

DFIG parameters
apparent power $S_{\mathrm{nom}} = 1\mathrm{MVA}$;
power factor =0.9
f_n =50Hz, $V_{s\text{-}n}$ =415 V (line-line,rms)
mutual inductance $L_{\mathrm{m}} = 2.9$ p.u.;
stator leakage inductance $L_{\mathrm{S}} = 0.18$ p.u.;
rotor leakage inductance $L_{\mathrm{r}} = 0.16$ p.u.;
stator resistance $R_{\mathrm{s}} = 0.023$ p.u.;
rotor resistance R_{r} =0.016 ;
pole number p =4;
Sen Transformer parameters
Apparent power $S_{nom} = 1\mathrm{MVA}$;
Voltage ratio $a = 1$
Magnetization inductance Lm = 600 p.u.;
Magnetization resistance R_{m} =600 p.u.;
Primary leakage inductance $L_{\mathrm{S}} = 0.01$ p.u.;
Secondary leakage inductance $Lr = 0.01$ p.u.;
Primary winding resistance $R_1 = 0.008$ p.u.;
Secondary winding resistance R_2 =0.008 p.u.;
MLC based DVR
Series voltage controller parameters

$Kp = 60$ Ki =1400

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