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An LVRT Solution for DFIG Wind Turbine during Symmetrical Grid Fault by using "Sen" Transformer

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Abstract

Due to fuel crisis and increasing power demand, present days the power grid is interconnected with various renewable energy sources, among them wind energy is a vital and gifted source. DFIG is highly developed wind turbine generator due to their simplicity and low cost but the Power electronic convertors of DFIG are very sensitive to grid side faults. This article presents a new control approach with "Sen" Transformer (ST) for DFIG attached to grid at the time of faults. This ST is used to increase the voltage level of the stator to create the necessary magnetic field to maintain the rotor current under its transient rating. The Microcontroller Based Controlled Unit (MBCU) is monitors the voltage at grid and compensates the required voltage by changing proper taping of ST for continuous operation of DFIG. Simulation results disclose the rotor currents of DFIG stayed within acceptable range for Low Voltage Ride Through.

Keywords: DFIG Wind Turbine, LVRT, MBCU, ST, Series Voltage Compensation, Symmetrical Grid Fault

1. Introduction

In the middle of renewable power sources, wind power is better and is projected to play a main position in the prospect power group. DFIG is one of the highly developed wind turbine generator due to robustness and capable to regulate unreal power. The disadvantages of using this type of induction generators are their susceptibility to grid side sudden change of voltages and it employs electronic converters to change the real and unreal power on grid side. The rotor side currents will increase when fault occurs on the grid side and if it is not confined against these abnormal, it leads to spoiled[1]. DFIG wind turbine offers as one of the options for generating electricity. Due to its slow rotation with the speed of 30-50 rev/min, the speed should be increased up to 1000-1500 rev/min using gears for directly integrating to grid[14]. According to the WECC regulation, any device particularly DFIG has to remain online if a 3-Ø short circuit happens in the line and very before for 0.15 s go after by access ramp voltage reconstruct to 90% of rated value in 2.85s (Figure 2). Present days, many investigators have paying attention on various techniques to beat the lower voltage issue[2,3]. One of the techniques is rotor clamp circuit[4]; the asynchronous machine consume a lot of unreal power from the grid throughout short circuit period for build up the voltage which is fall down by fault. Moreover, when the DFIG is running in above rated speed, voltage across on capacitor spectacularly raises. At that time this path does not offer any solution to save this capacitor. An extra circuit is desirable to lesser the dc-link voltage[4]. In this article, we present a solution to use a "Sen" Transformer[5,6] on grid side of a DFIG to ease the consequence of the symmetrical fault on the turbine.

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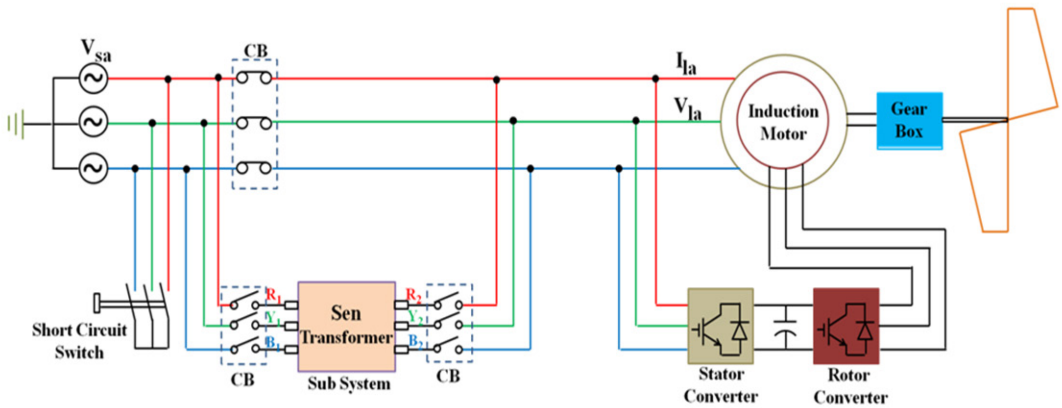

Figure 1. Configure ration of "Sen" Transformer.

This transformer, as shown in Figure 1, acts as a series voltage restorer for voltage restoration. This 'Sen' Transformer has two main units one of them is exciting unit and another one is compensating unit. Exciting unit linked in parallel with grid terminals and compensating unit linked in series with the stator side terminals as shown in Figure 3, the "Sen" Transformer (ST) injects the required voltage under fault condition to tone down the effect of fault in DFIG. This transformer not needs to recompense of full line voltage during fault. Usually, this equipment on the rotor can stand up to 3 times of its actual current in passing state. Hence, the ST can be planned at perceptible rating well below the power rating of the WG.

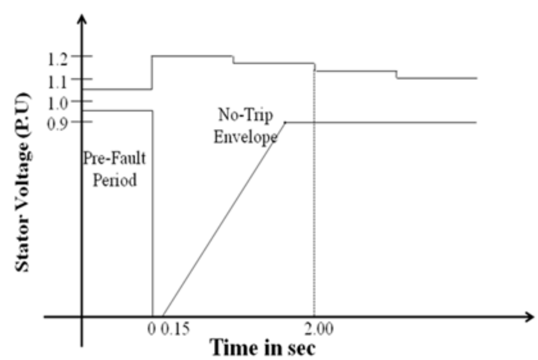

Figure 2. Projected WECC code for LVRT necessities for generators.

2. "Sen" Transformer (ST)

The Figure 3 shows diagram of ST. It consists of two main parts, one is the excitation winding component and second one is the restoring component. The restoring component has 9 compensated windings, 3 from 'R' phase, 3 from 'Y' phase and another 3 from 'B' phase. These compensated windings are organized to get entire 360^0 of process. It is the major benefit of ST. Therefore it is able to add restoring voltage in series with line from 0^0 to 360^0.

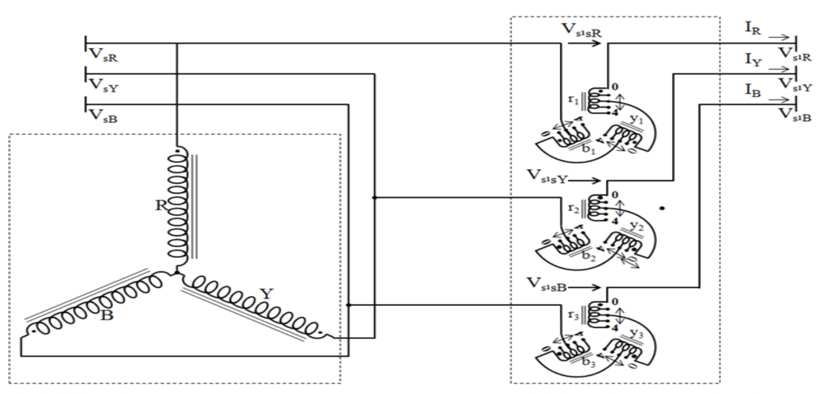

Figure 3. Schimatic diagram of Sen Transformer.

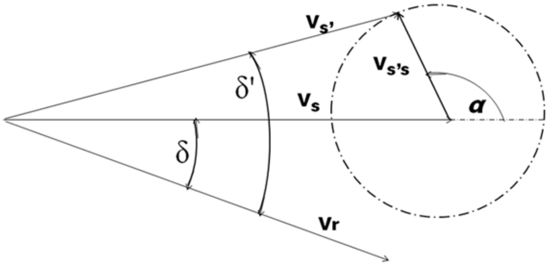

Figure 4. Phaso diagram of Sen Transformer.

Figure 4 shows phasor diagram of ST, where a restoring voltage $V_{S'S}$, from ST added to the phase voltage V_s at an angle α(leading), to produce the resultant voltage $V_{s'}$. The angle α can be varied between 0° and 360°. If any voltage disturbance is occurs in the system the better grouping of the tap positions which gives the restoring voltage $V_{S'S}$[6]. By this way it can sustain the stability of the wind power system by using ST.

The designed solution ST is use as a series regulator which defends the rotor circuits of DFIG wind turbine from all stator side faults. Figure 1 shows the connection of ST between the source and DFIG wind turbine through breakers. For the duration of regular working circumstances, ST is off position. During fault time, the ST operates in active and injects required voltage for stable operation.

3. Analysis of DFIG throughout Grid Fault

Various references have talked about modelling of DFIG[7,8]. Figure 1 shows the Schematic figure of DFIG with ST. A mathematical model in fixed stator reference frame developed for DFIG in[9]. In this representation, the rotor parameters are referred to the stator side. In motor convention, both Vs and Vr can be written as

$$\overrightarrow{v_s} = R_s \overrightarrow{i_s} + \frac{d}{dt}\overrightarrow{\psi_s} \quad (1)$$

$$\vec{v}_r = R_r \overrightarrow{i_r} \frac{d}{dt}\overrightarrow{\psi_r} - j\omega_m \overrightarrow{\psi_r} \quad (2)$$

Both stator and rotor fluxes are

$$\overrightarrow{\psi_s} = L_s \overrightarrow{i_s} + L_m \overrightarrow{i_r} \quad (3)$$

$$\overrightarrow{\psi_r} = L_r \vec{i}_r + L_m \vec{i}_s \quad (4)$$

Here $L_s = (L_{1s} + L_m)$ and $L_r = (L_{lr} + L_m)$

$\vec{V}$	current vector
r, s	subscript denote rotr and stator.
L_m	Magnetizing inductance.
L_r, L_s	Self-inductances of rotor and stator.
L_{1r}, L_{1S}	Leakage inductance of rotor and stator.
R_r, R_s	Rotor and stator resistence
V	Voltage vector
$\vec{v}_{s-n}$	Vector of normal stator voltage.
$\vec{\psi}$	Flux per pole.
$\vec{\psi}_{s-n}$	Nominal state stator flux.
ω_m, ω_s, ω_r, frequencies.	Rotor, synchronous and slip angular
τs	Stator time constant.
ρ	Leakage factor.
VS	Nominal grid side voltage
V_s	Grid side voltage after compensation.
$V_{s's}$	Compensated voltage with ST.
R, Y, B	Subscript denoting phases R, Y and B.

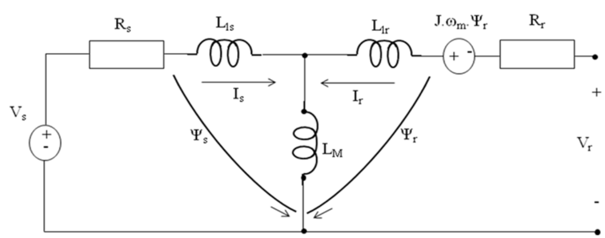

Figure 5. Equivalent circuit of DFIG for fault analysis.

The above figure 5 subsequent to the aforesaid equations for the point of rotor transient current investigation throughout a fault, the rotor side voltage is the most significant parameter in this investigation[9]. From Equation (3) and place into Equation (4)

$$\vec{\psi}_r = \frac{L_m}{L_s}\vec{\psi}_s - \rho L_r \cdot \vec{i}_r \quad (5)$$

$$\textit{Here } \rho = 1 - \frac{L_m^2}{L_s \cdot L_r}.$$

Thus, the voltage of rotor found by look at (2) & (5) a

$$\vec{V}_r = \vec{V}_s \frac{L_m}{L_s} s + \left(R_r + \rho L_r\left(\frac{d}{dt} - j\omega_m\right)\right)\vec{i}_r. \quad (6)$$

The voltage of the rotor is known by Equation (6) is separated into two parts. The initial expression is the OC voltage $\vec{V}_{ro}$ and it is proportional to stator magnetic flux.

The next expression is lesser and it depends on both Rr and ρLr. From Equation (6), if current is not available in the rotor circuit, then the rotor voltage is

$$\vec{v}_{ro} = \frac{L_m}{L_s}\left(\frac{d}{dt} - j\omega_m\right)\vec{\psi}_s. \quad (7)$$

3.1 Examination under Nominal Operation

Under nominal process, the voltage of the rotor is illustrated like

$$\vec{v}_r = \vec{v}_s \frac{L_m}{L_s} s + \left(Rr + \rho Lr\left(\frac{d}{dt} - j\omega_m\right)\right) i_r. \quad (8)$$

Here the slip $S = \omega_r/\omega_s$, $\omega_r = \omega_s - \omega_m$.

The rotor resistance Rr and ρLr are characteristically little. In totalling the induction machine slip is restricted from ±25% to ±35% and the rotor current frequency is fr ≤ 20 Hz[9]. So, the amplitude of V_{ri} in Equation (8) is lesser than V_{ro}. Therefore V_{ro} in terms of magnetic flux is

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

The magnitude of the rotor voltage interms of stator voltage is

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

Throughout this usual process, V_{ro} is proportional to V_s and slip(s) of DFIG.

3.2 Examination of DFIG during Fault

At the instant of fault, V_{ro} is

$$\vec{v}_{ro} = -\frac{L_m}{L_s}\left(\frac{1}{\tau_s} + j\omega_m\right).\vec{\psi}_o.e^{-t/\tau_s} \quad (11)$$

Here $\vec{\psi}_o$ is the stator magnetic flux just before the fault

$$\text{i.e } \vec{\psi}_o = \frac{V_s}{j\omega_s} e^{j\omega_s t_o} \quad (12)$$

With respect to the rotor, this rotor voltage revolves negatively with ωm.

$$\vec{v}_{ro} = -\frac{L_m}{L_s}\left(\frac{1}{\tau_s} + j\omega_m\right).\vec{\psi}_o.e^{-t/\tau_s} e^{-j\omega_m t} \quad (13)$$

Using (13) 1/τs term is neglected ($\tau_s \approx 1s - 3s$)[10, 11], now

$$V_{ro} = \frac{L_m}{L_s}\frac{\omega_m}{\omega_s} V_s = \frac{L_m}{L_s}(1-S)V_s. \quad (14)$$

From Equation (14), the rotor voltage nearer to stator voltage.

3.3 Examination of DFIG under Incomplete Voltage Dip

In this examination, we imagine that the machine is operating at the normal voltage, when at time (t) equal to zero the stator voltage is

$$\vec{v}_s = \begin{cases} \vec{v}_{s-n}, & \text{for t less than zero} \\ \vec{v}_s, & \text{for t greater than zero} \end{cases} \quad (15)$$

$$\vec{v}_s = r_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt}. \quad (16)$$

Solving for $\vec{i}_s$ from Equation (3) and substitute into Equation (16) give up

$$\frac{d\vec{\psi}_s}{dt} = \vec{v}_s - \frac{r_s}{L_s}\vec{\psi}_s. \quad (17)$$

Neglect Rs, therefore the flux is

$$\vec{\psi}_{s-n}(t \le 0) = \frac{\vec{v}_{s-n}}{j\omega_s} \quad (18)$$

Replacing phasor of $\vec{v}_{s-n}$ with $\vec{v}_{s-n} e^{j\omega_s t}$ we get

$$\vec{\psi}_{s-n}(t \le 0) = \frac{\vec{v}_{s-n}}{j\omega_s} e^{j\omega_s t} \quad (19)$$

Here K is the ratio of the stator side voltage at previous and after the sag

$$K = \frac{|\vec{v}_s|}{|\vec{v}_{s-n}|}. \quad (20)$$

Neglect the stator resistance, if sag occurs at t = 0 then the response $\vec{\psi}_s(t)$ is

$$\vec{\psi}_s(t) = \frac{v_s}{j\omega_s} e^{j\omega_s t} + \left(\frac{v_{s-n} - v_s}{j\omega_s}\right) e^{-\left(t/\tau_s\right)} \quad (21)$$

By using Equation (19) and Equation (20), the $\vec{\psi}_s(t)$ is

$$\vec{\psi}_s(t) = \vec{\psi}_{s-n}\left(K + (1-K)e^{-(j\omega_s + (1/\tau_s))t}\right). \quad (22)$$

By depute Equation (22) into Equation (7), the rotor voltage is

$$\vec{v}_{ro} = |\vec{v}_{s-n}| \frac{L_m}{L_s}\left(K.s.e^{j\omega_s t} - (1-K)(1-s)e^{-\left(t/\tau_s\right)}\right). \quad (23)$$

Equation (23) is the voltage at rotor side when there is no rotor current. On the other hand, throughout the regular process, the rotor voltage is

$$\vec{v}_{ro} = |\vec{v}_{s-n}| \frac{L_m}{L_s}(K.s.e^{j\omega_s t} - (1-K)(1-s)e^{-(t/\tau_s)} + (R_r + \sigma L_r(\frac{d}{dt} - j\omega_m))\vec{i}_r. \quad (24)$$

4. Proposed Result

At t equal to zero a 3-Ø symmetrical fault takes place

$$V_s = V_{s-n}, \quad \text{for t less than zero.}$$

$$V_s = V_{s'}, \quad \text{for t greater than zero} \quad (25)$$

At this condition the rotor voltage when t = 0 Equation (23) is re write as

$$V_{ro} = |V_{s-n}| \frac{L_m}{L_s}(K.s - (1-K)(1-s)) \quad (26)$$

$$= |V_{s-n}| \frac{L_m}{L_s}.K.s - |V_{s-n}| \frac{L_m}{L_s}(1-K)(1-s).$$

Equation (26) having two different terms. The 1st term is

$$|V_{s-n}| \frac{L_m}{L_s}.K.s = V_{s'}.\frac{L_m}{L_s}.s \quad (27)$$

Therefore this voltage induced by new stator side voltage magnitude is small due to slip S. And another part of Equation (26) is

$$|V_{s-n}| \frac{L_m}{L_s}(1-K)(1-s) \quad (28)$$

$$= |V_{s-n}| \frac{L_m}{L_s}(1 - \frac{|\vec{v}_s|}{|\vec{v}_{s-n}|})(1-s)$$

$$= |V_{s-n}| \frac{L_m}{L_s}(\frac{|V_{s-n}| - |V_s|}{|V_{s-n}|})(1-s)$$

$$= \frac{L_m}{L_s}(|V_{s-n}| - |V_s|)(1-s)$$

Its magnitude is relative to the deepness of sag i.e., 1–s. This voltage causes increase enormous current in rotor circuit.

If sag is compensated then h becomes equal to one in Equation (26) then the second part of Equation (26) will be removed. In this paper accomplish this goal by using Sen Transformer as a voltage compensator.

As shown in Figure 1 during fault condition the line CB and ST CBs are operate for restoring voltage is added to grid side voltage to tone down the dip. Therefore the grid side voltages is

$$V_{s'} = V_s\angle 0 + V_{s's}\angle\alpha \quad (29)$$

Where V_s is new grid side voltage per phase nearly equal to normal voltage $V_{s\text{-}n}$ per phase and the angle α controls the reactive power of the power system. Before compensating h is less than one, it depends upon the severity of voltage sag on grid side. After compensation the value of h is equal to 1. Therefore above Equation (26) yields to

$$V_{ro} = V_{s'} \frac{L_m}{L_s} s \quad (30)$$

Previous equation describes the rotor side voltage when Ir = 0. On other hand, in usual condition, the rotor side converter controls the current in order to attain the reference real and unreal powers. The rotor side converter voltage is

$$V_r = V_{s'} \frac{L_m}{L_s} s + (R_r + \rho L_r(\frac{d}{dt} - j\omega_m))\vec{i}_r. \quad (31)$$

The generated voltage V_r in the rotor due to stator field does not go beyond its normal value. The simulation result tells the usefulness of the proposed solution for custody the rotor current below rated value at the instant of fault condition.

5. Control Method

In this fragment, the technique for the ST is explained. The appliance of the power electronic switches in on-load taping circuit of a transformer has the advance of fast response[12]. The compensating unit of ST has nine 1Ø transformers; each one of the secondary has 4 taps, as a result the total tapings of ST is 45. But, many practical conditions 360^0 voltage injection is not required[13]. Figure 4 shows the schematic diagram of MBCU based on load tap changer for ST. For limited angle operation 6 single phase transformers are sufficient to compensate the required voltage, as a result total number of taps of ST is 30. Each tap is connected with power electronic switch GTO. The controlled signals for these GTOs are taken from MBCU. The MBCU is sheltered from the system voltage by using opto-couplers with low voltage circuit. The MBCU is used for controlled the GTOs as per the code inhabited in the controller. So, there is a change in the output voltage from the reference the MBCU know the deviation immediately sends signal to the GTO to switch ON as per the program inhabited.

6. Analysis of DFIG during Grid Fault without ST

According to IEEE recommended practices and requirements a voltage dip/sag is an unexpected drop between 10% and 90% of the voltage at appoint in the electrical power system, which lasts for half a cycle to 1 min. Many causes for a voltage dip: Switching operations related with a temporary disconnection of power, short circuit faults on grid side, and the flow of the serious currents that are caused by the start of large motor loads.

The authenticate investigative and simulation analysis, a new unit was built and tested.

The MATLAB/SIMULINK diagram of the test setup is shown in Figure 7. Here, the DFIG is part of an offshore wind farm and that the voltage sag happens 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 Figure 8 and 9 the stator voltage fall down from 100% to 30% and in Figure 10, the rotor current increases nearly 4 times during short circuit. The Figure 7 shows, a power system connected with DFIG with 3-Ø source voltage and three phase symmetrical fault and without "Sen" Transformer (ST).

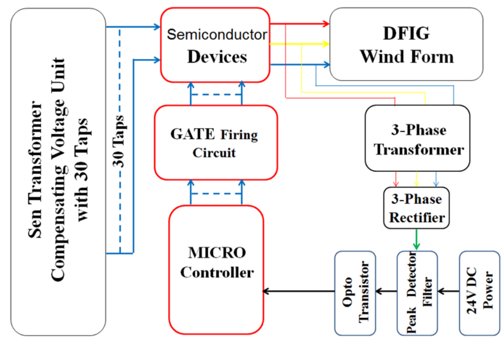

Figure 6. Block diagram for automatic tap changing unit of ST with DFIG.

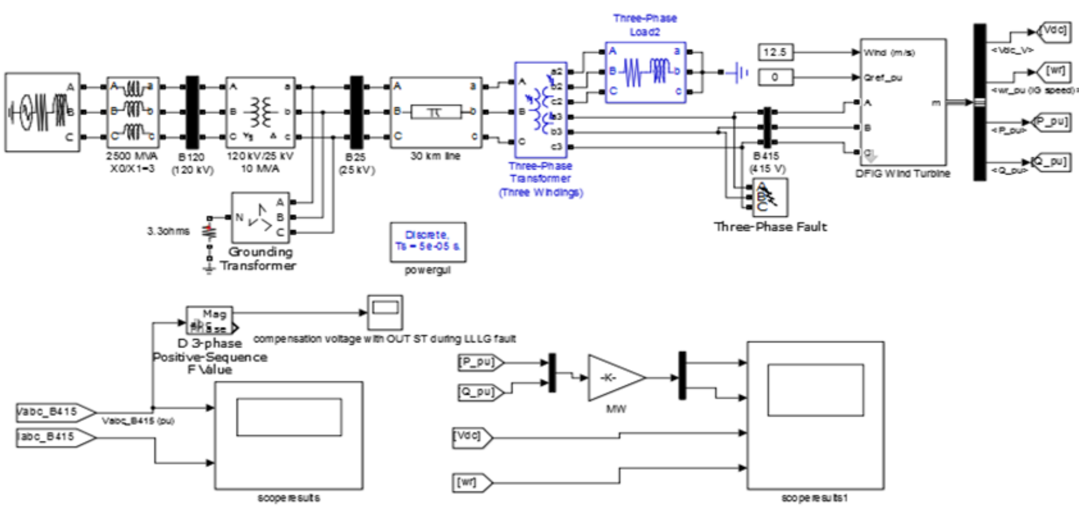

Figure 7. Simulink diagram of DFIG during short circuit without ST.

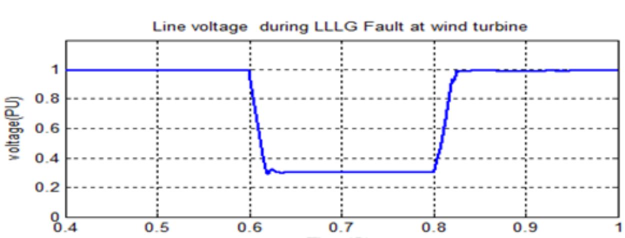

Figure 8. Stator voltage of DFIG during fault condition without ST.

The Figure 8 shows the voltage sag/dip at stator side with symmetrical fault without ST.

The Figure 9 shows the voltage and currents in per unit at stator side with symmetrical fault without ST.

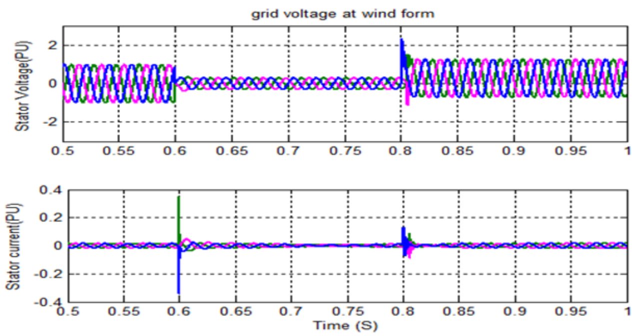

Figure 9. Grid side voltage and current during fault condition without ST.

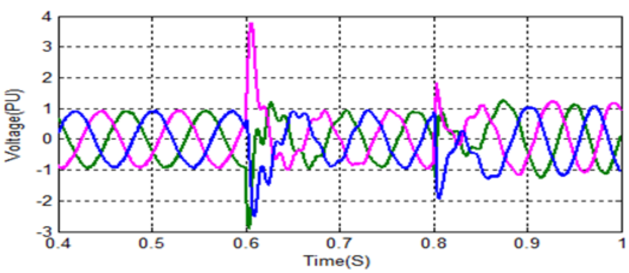

Figure 10. Rotor side converter current without ST.

The Figure 10 shows the rotor side converter currents with grid fault without ST.

The Figure 11 shows the simulation results of DFIG at variation of real and unreal power, dc voltage and rotor speed from normal state through fault condition without ST.

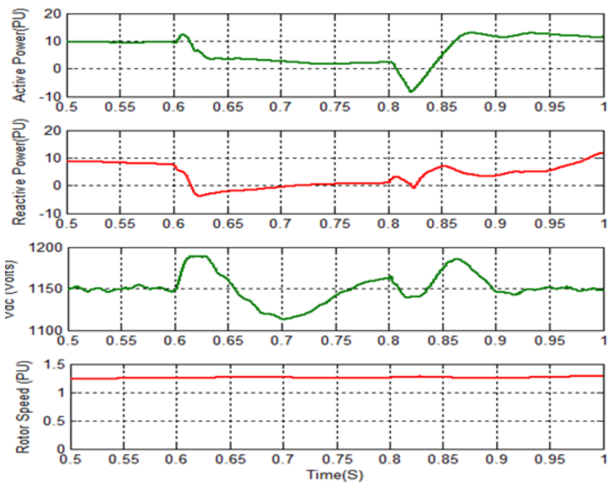

Figure 11. Symmetrical fault on the terminal of DFIG wind turbine without ST.

7. DFIG Wind Turbine through Grid Fault with ST

In this fragment, explanation will be given of a technique that has the objective to keep the DFIG associated to the grid in case of malfunction of grid.

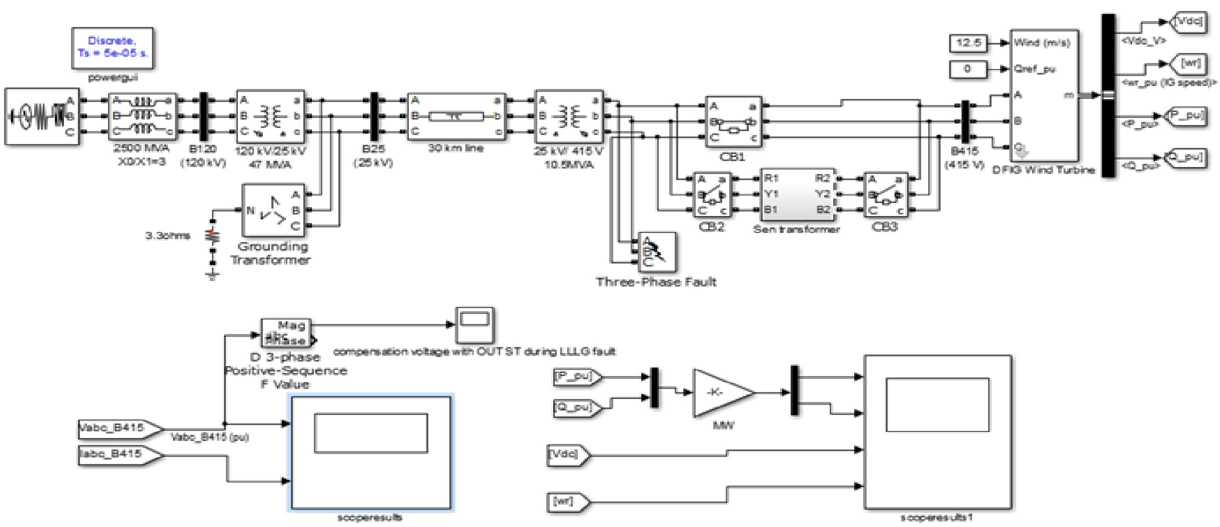

Figure 12. DFIG wind farm with ST and LLLG fault.

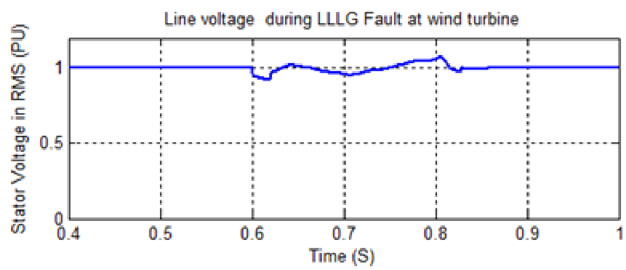

Figure 13. Stator voltage in RMS with ST.

In Figure 12, 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 second to 0.8 second. Figure 13 and Figure 14 show the system behaviour during the symmetrical fault with almost full stator voltage compensation. Therefore, the fault does not have any major impact on rotor side current and dc link voltage as shown in Figure 15 and Figure 16.

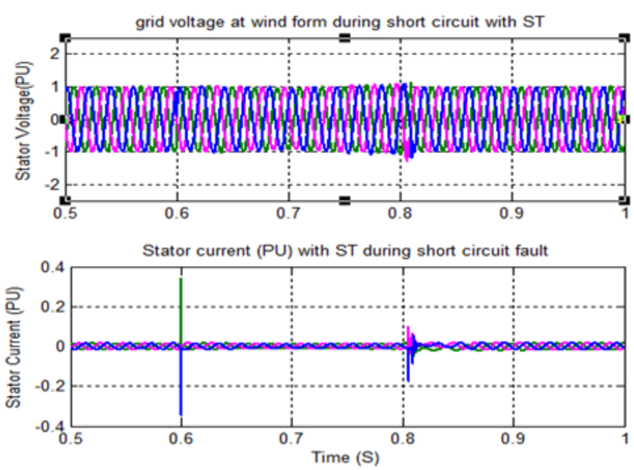

Figure 14. Stator voltage and current with ST.

The above figure shows stator voltage and currents are stable at stator side during grid fault with ST.

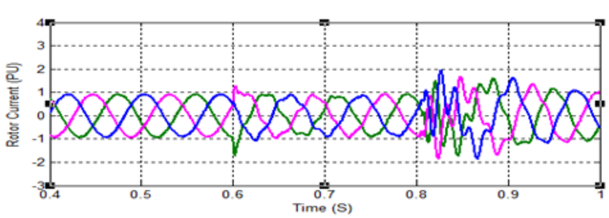

Figure 15. Rotor current within normal range during fault with ST.

The Figure 15 shows the rotor current keep on its regular value with little transient due to interruption in voltage insertion.

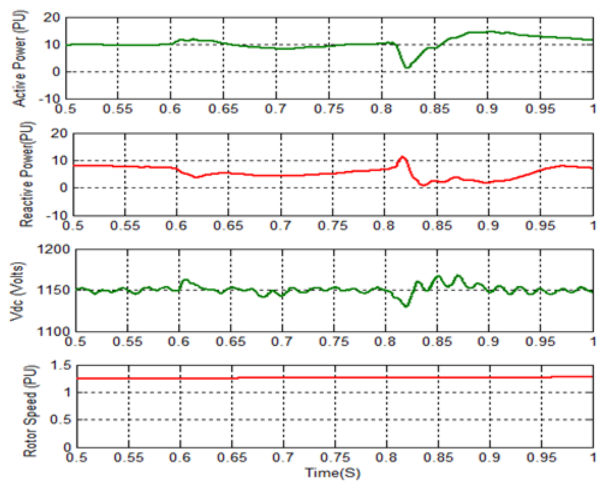

Figure 16. DFIG wind turbine with ST under fault condition.

Figure 16 shows active power, reactive power and voltage across capacitor and rotor speed are in stable during fault with series voltage compensation by using ST.

8. Discussion

This article investigates the behavior of the DFIG through fault without voltage compensation and with compensation in the system network by using ST. From Section 6, it is observed that when fault is occur then the stator side voltage fall down almost 70% without ST as shown in Figure 7, according to Equation (26) the rotor side current is proportional to depth of the sag. Therefore the rotor side current enormously increases from 100 % to 380 % as shown in Figure 9. In general, during transient condition the equipment of the rotor be able to bear up to 300% of its rated current. So in this state ride-through is not possible. From Section 7, as shown in Figure 12 the ST is compensated full voltage then as shown Figure 14 the rotor side current is reduced from 380 % to 120 % within the acceptable range. From references, currently Voltage Sourced Convertor (VSC) based Dynamic Voltage Restorer (DVR) is capable to ride-through the DFIG wind turbine during grid fault effectively[1]. The proposed method not required dc link, as a result there is no restriction about Compensation time and there is no harmonic production during normal working condition.

The proposed method neither uses inverter stage nor rectifier stage and GTOs be used as controlled switches, resulting in a considerable cost reduction. The GTOs operated when switching state is needed.

9. Conclusion

Doubly fed induction generator is focused to deep pressure throughout substantial grid side sudden voltage drop. Extra procedures have to take to guard the WT (Wind Turbine) and grant ride-through in accord with service requirements. Wind turbine set with ST as a voltage restorer is capable to keep on coupled to the grid and limits the rotor currents with in an adequate assortment. At present sen transformer was operated as static reactive and active power compensator, now a LVRT solution for DFIG wind turbine through short circuit faults. It allows unreal power support to the grid throughout fault. For longer voltage dips also, the ST is ride-through the system. Simulation results prove the efficiency and possibility of the projected method.

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Appendix

The DFIG and Sen Transformer parameters that have been used during the simulations are given below. All circuit parameters are mentioned in per units.

DFIG parameters.
Apparent power S_{nom} = 1MVA.
Power factor = 0.9.
f_n =50Hz, V_{s-n} = 415 V (line-line, rms).
Mutual inductance L_m = 2.9.
L_S = 0.18, L_r = 0.16.
R_s = 0.023 and R_r = 0.016.
Pole number p = 4.
Sen Transformer parameters.
Apparent power S_{nom} = 1MVA.
Voltage ratio a = 1.
Magnetization inductance L_m = 600.
Magnetization resistance R_m = 600.
Primary L_S = 0.01, Secondary L_r = 0.01.
Primary R_1 = 0.008, Secondary R_2 = 0.008.