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Mitigation of Unbalanced Voltages for Grid Connected DFIG Wind Farms with Sen Transformer

B. Loveswara Rao* and P. Linga Reddy*

Abstract: The effect of unbalanced voltage in the grid connected DFIG wind turbine may cause problems like excessive losses and mechanical oscillations. The voltage unbalance causes imbalance in current also. The temperature rise due to unbalance in currents is higher than due to unbalanced voltages. The voltage imbalance can also negatively affect the turbine torque and speed. So the generator may produce excessive noise. Therefore the efficiency and life time of the DFIG wind turbine is reduced. To overcome these problems automatic tap changing Sen Transformer is used. In this paper the effect of unbalanced voltages at DFIG has been studied. MATLAB/SIMULINK Results show that the Sen Transformer mitigates unbalanced voltages effectively.

Keywords: Unbalance Voltage; DFIG-Wind Turbine; Automatic Tap Changing Sen Transformer (ATC-ST).

1. INTRODUCTION

In recent years, electricity production under renewable energy sources has increased considerably. By the end of 2014, power production from renewable energy sources worldwide exceeded 1712 Giga watt (GW) representing approximately 20% of global energy consumption [1]. The cumulative installed wind power capacity increased exponentially from 16.1 GW in 1996 to 432.4 GW by 2015. If it continues the trend the cumulative wind capacity would reach 760 GW by 2020 [2]. So it is necessary that, wind generating plants behave like conventional power plants to sustain reliability of the power system.

The unbalanced voltages give a bad influence for the power quality. From 1990's DFIG is one of the leading generators for wind power. The unbalanced voltages overheat the induction machine. In this paper the effect of unbalance for grid connected wind farms is analyzed and a proper solution is proposed for mitigating the unbalanced problems. According to NEMA and IEEE standards [3], [4], the voltage unbalance is computed by the following equation

$$\text{\% of unbalance voltage} = \frac{\text{Maximum voltage deviation from average voltage}}{\text{Average voltage}} \times 100 \quad (1)$$

2. DFIG WIND FARM DURING UNBALANCED VOLTAGES

The modeling of DFIG wind turbine explained in many references during unbalanced condition [5], [6], [7]. Unbalanced grid voltage impacts the induction generator and it could also have an effect on the everyday operation of the DFIG converter in an unfavorable manner. Beneath such an odd situations, wind mills may be disconnected from the grid for their personal protection, extensively impacting their power manufacturing. Voltage unbalance will immediately have an effect on the stator windings and also the normal operation of the grid side converter.

The grid side converter is designed to accept a balanced 3 phase deliver voltage and the control of the DC link voltage inside the converter is based in this assumption. Voltage unbalance impacts the operation of the grid aspect converter resulting in DC link voltage oscillations.

* Department of EEE, K.L. University, Guntur - 522502, A.P, INDIA. *Email: loveswararao@kluniversity.in; lingareddypotla_eee@kluniversity.in*

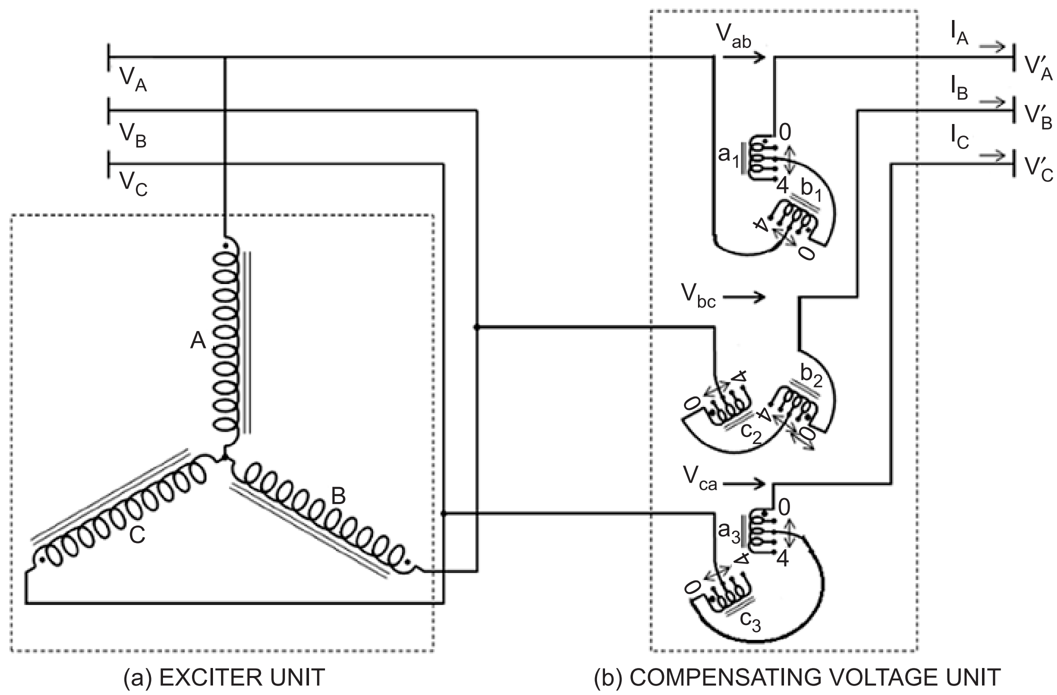


Figure 1: Sen Transformer configuration

The maximum important problems which can be experienced by DFIG's at some point of grid voltage unbalance are [8]:

Rotor abnormal current hazards the rotor converter.

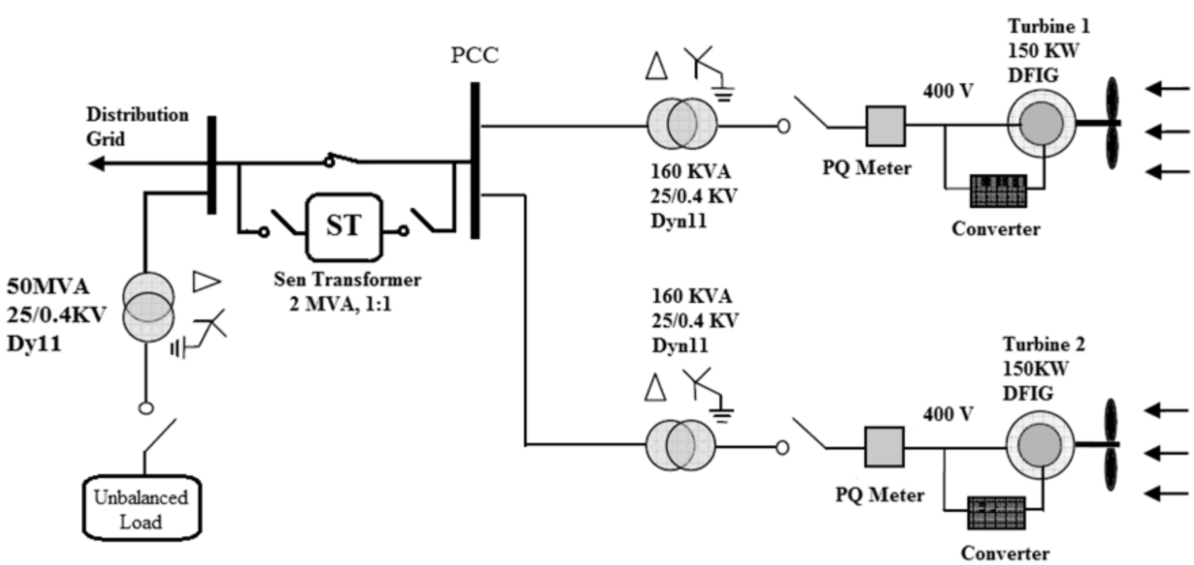
DC hyperlink over voltage and capacitor failure.

Temporary loss of control of turbine real and imaginary power output.

Energy and shaft torque oscillation causes generator damage.

Stator and rotor unbalanced currents lead to uneven heating which reduce the life time of the generator.

To overcome all these problems Sen Transformer is used. A single line diagram for DFIG wind farm with Sen Transformer (ST) is shown in Figure 2(a).



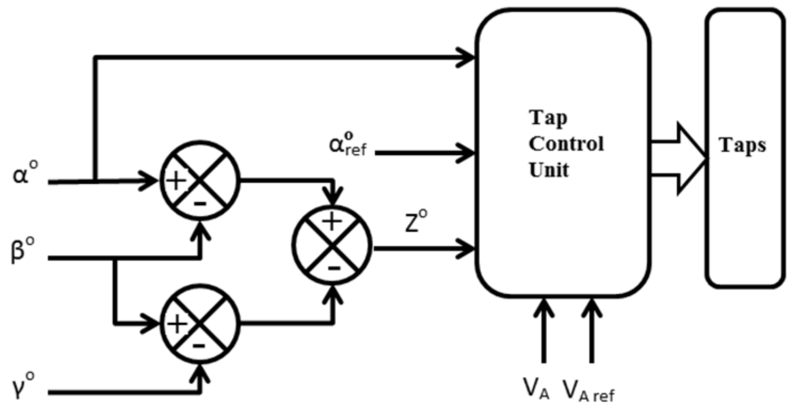


Figure 2: (a) Single line diagram for DFIG Wind Farm with ST. (b) ST Tap Control Unit.

3. AUTOMATIC TAPCHANGING SEN TRANSFORMER

K K Sen proposed a multi winding Transformer for control both active and reactive powers in transmission lines independently. Sen Transformer [ST] is a set of efficient power flow controller [9], [10], [11]. It has two main units one is excitation unit and another one is compensating unit as shown in Figure 1. It has the capability to ride through the DFIG wind turbines during low voltage [12]. Compare to existing devices like DVR, D-STACOM the Sen Transformer is cost effective [13],[14]. For limited angle operation nine winding compensating voltage unit is not required. The proposed method ST uses only six windings in compensating unit. Each winding have four taps, for total six windings have only 24 taps. All taps inbuilt with power electronic switches. In the proposed solution GTOs (Gate Turn Off) are used as tap changing switches [15], [16]. All taps are controlled by programmable tap controller (PTC).

Out of 24 taps only 6 taps will be triggered. Every phase of ST having their own PTC. The Figure 2(b) shows the PTC for phase A, in this figures α_0, β_0 and γ_0 are angle between reference phase to phase A, phase B and phase C respectively. Here the value of Z_0 tells weather the phase angles of the system are balanced or unbalanced. For example if $\alpha_0 = 0°$, $\beta_0 = -120°$ and $\gamma_0 = -240°$ then the Z_0 value is zero i.e., the system voltage phase angles said to be balanced. Under symmetrical, the PTC only regulates the voltage magnitude. When the system is unbalanced, the PTC regulates both magnitude and phase angle.

4. SIMULATION RESULTS AND ANALYSIS

As shown Figure 2(a), two 150 KW, 400 V DFIG wind turbines are inter connected with 25 KV distribution grid through 160 KVA, 25 KV/0.4 KV distribution transformers along with ST. Entire arrangement is inbuilt with MATLAB/SIMULINK environment with programmable tap controller which is in built with MATLAB function generator.

4.1. Without Sen Transformer

Figure 3. Shows the SIMULINK diagram of grid interconnected DFIG Wind farm without ST. Under normal working condition the grid voltages are symmetrical but due to unbalanced load the line voltages are deviated from symmetry. Without compensator the simulation results of DFIG wind farm shown in Figure 4.The unbalanced load is activated at 0.4 second and deactivated at 1.1 second.

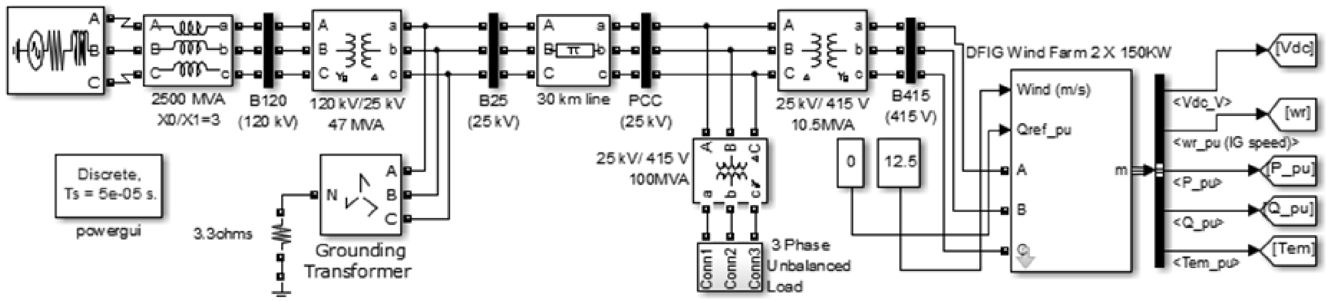


Figure 3: Grid interconnected DFIG Wind Farm without ST

The Figure 6 explains the total phasor analysis of the system. The Figure 6(a) shows referenced balance voltages as V_{AR}, V_{BR} and V_{CR}. Figure 4 shows the distribution system voltage waveforms without compensator and in Figure 6(b) the same voltages represented as V_A, V_B and V_C which are unbalanced. In this case the line voltages at PCC (Point of common coupling) are

$$V_A = 0.89 \angle{-180°};\ V_B = 0.7 \angle{-120°}\ \&\ V_C = 1.001 \angle{-239°} \tag{2}$$

The per unit average voltage for this condition is 0.863 pu and voltage V_B is more deviated from this value that is 0.163 pu. According to equation (1) voltage unbalance is 19%.

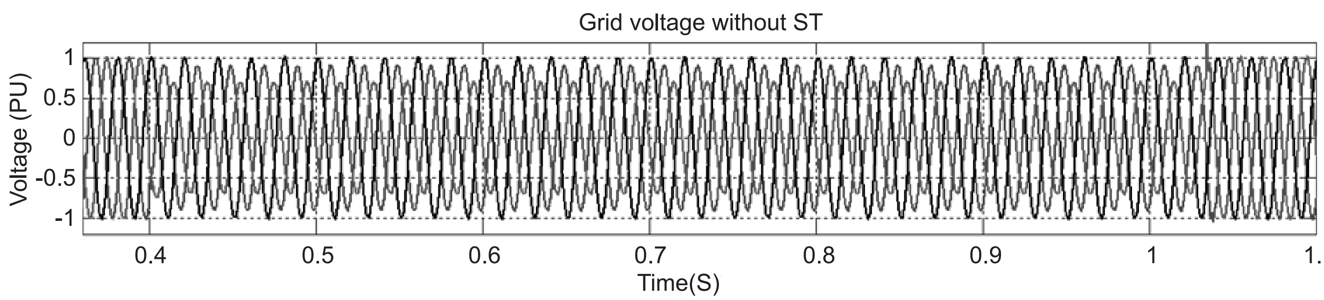


Figure 4: Grid voltages at PCC due to effect of Unbalanced load

The Figure 5 shows how the DFIG parameters varied during unbalanced state. The main observations from this diagram are: (i) torque is pulsated due to negative sequence currents as shown in Figure 5 (e); (ii) DC link voltage is oscillating as shown in Figure 5(c). These two problems lead to damage the generator,

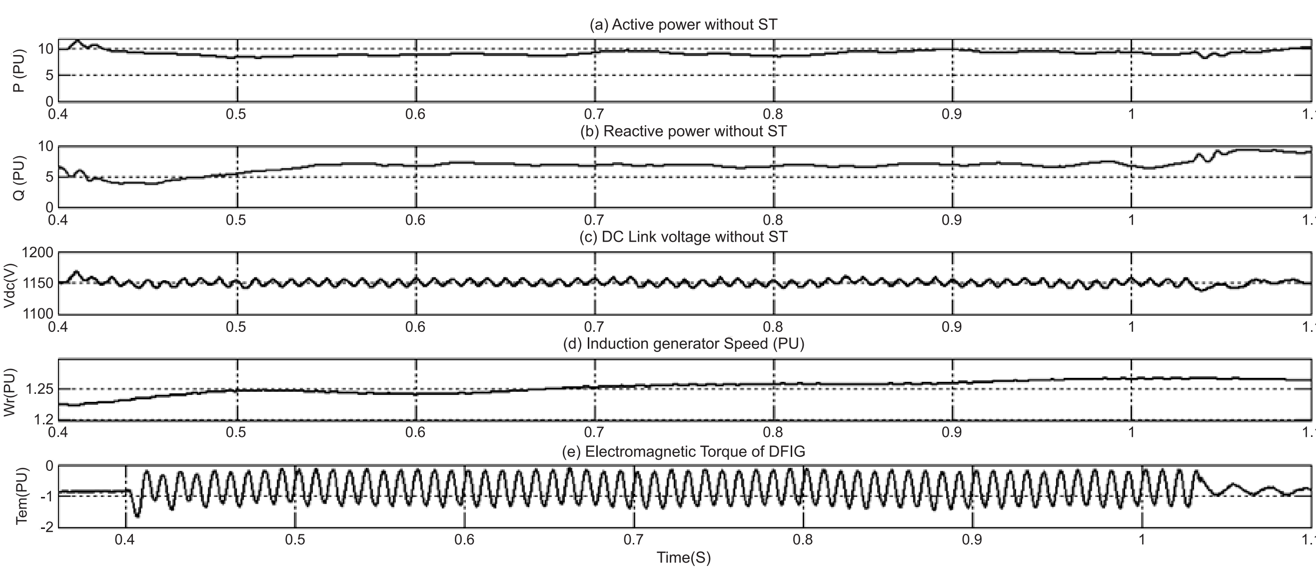


Figure 5: DFIG parameters under voltage unbalance

DC link capacitor and convertors. In addition to above problems it draws more reactive power (almost 5 times compares to normal state) from grid. It leads to trip the circuit that means the system is not capable to ride-through with Sevier unbalance.

4.2. With Sen Transformer

Figure 9. Shows the SIMULINK diagram of grid interconnected DFIG Wind farm with ATC-ST. The programmable tap controller always monitors the system phase voltages and compare with reference voltages. If any deviation is occurred beyond the tolerance (±10% for voltage magnitude and ± 4% for angle between the line voltages) the controller selects the proper tapings and gives the gate signals to the respective GTOs for injecting the required voltage to mitigate the unbalance.

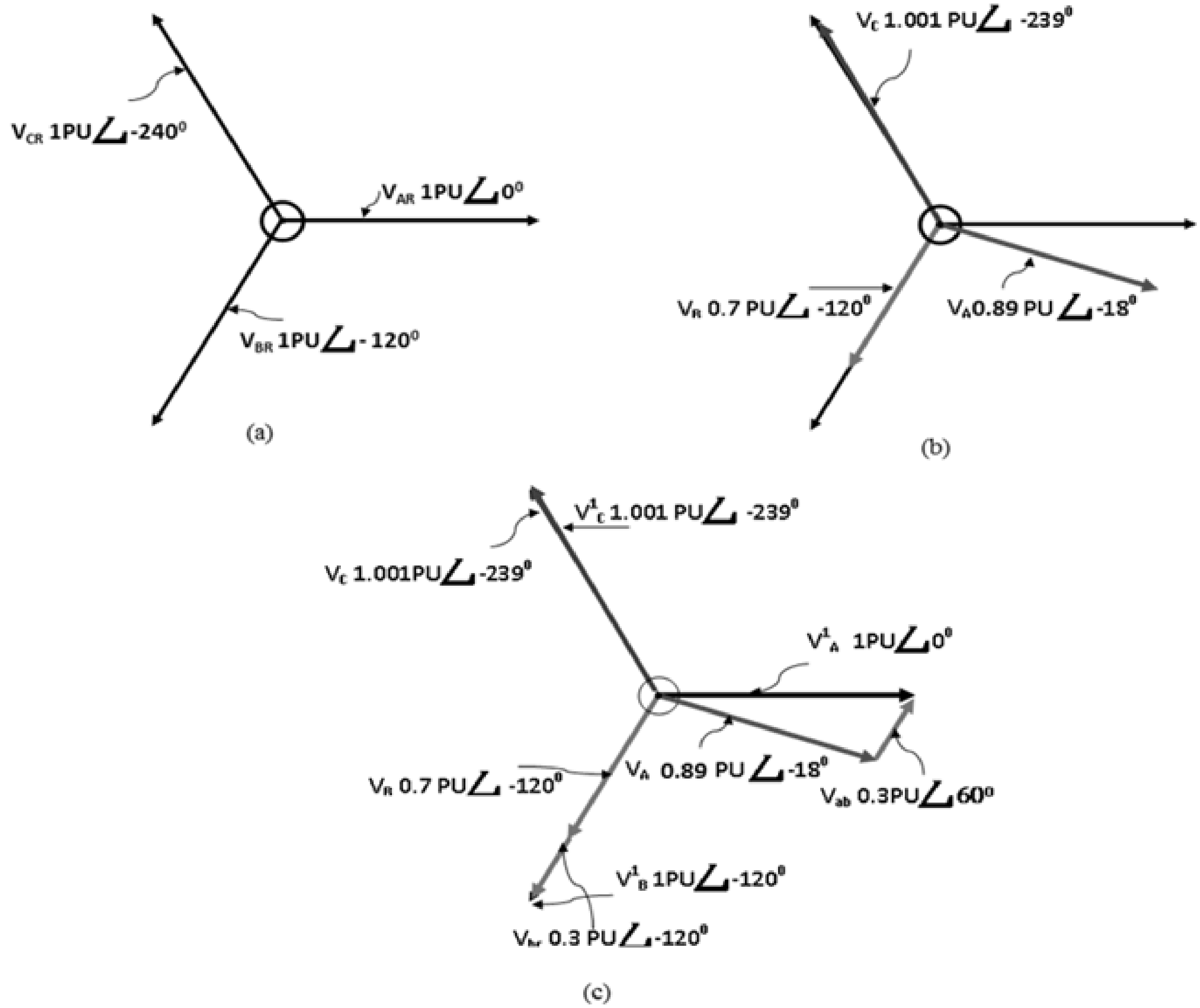


Figure.6: Phasor diagrams: (a) reference voltages, (b) Grid voltages at PCC due to unbalanced Load and (c) Mitigation of unbalance with Sen Transformer for DFIG wind farms

Therefore ST will be compensates required magnitudes and phase angles as shown in Figure 6(c). In this case the output voltages of ST are

$$V_A^1 = 0.89 \angle -18° + 0.3 \angle 60° = 0.996 \angle -0.87° \cong 1 \angle 0° \quad (3)$$

$$V_B^1 = 0.7 \angle{-120°} + 0.3 \angle{-120°} = 1 \angle{-120°} \quad (4)$$

$$V_C^1 = 1.001 \angle{-239°} \quad (5)$$

The Figure 7. Shows resultant voltage wave forms at PCC where DFIG wind farm is connected. After compensation the system average voltage is 1pu and maximum deviated voltage is 0.004 pu. So voltage unbalance is 0.4%. For effective operation under steady state this value can be upto 2%.

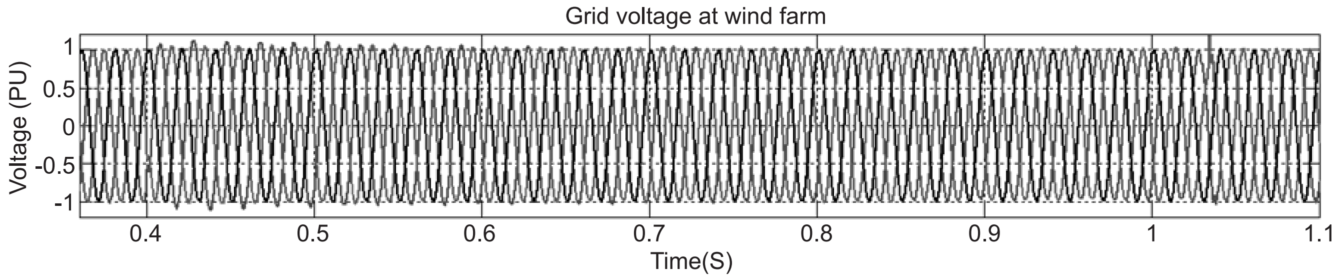


Figure 7: Grid voltage at wind farm with ST.

The Figure 8 shows how DFIG effectively generates power without disturbance after mitigation of unbalance. The main observations from these results are (i) from Figure 5(a) and Figure 8(a) after voltage unbalance mitigation, the DFIG wind turbine generates more active power because of reduction in loss due to absents of negative sequence currents. (ii) From Figure 5(b) and Figure 8(b) after mitigation DFIG draws less reactive power from grid (almost 5times reduced). (iii) From Figure 5(c) and Figure 8(c) after mitigation the DC link voltage oscillation is minimized. Figure 5(d) and Figure 8(d) indicates that the speed is same for both balance and unbalanced conditions therefore efficiency is increased after mitigation of voltage unbalance.

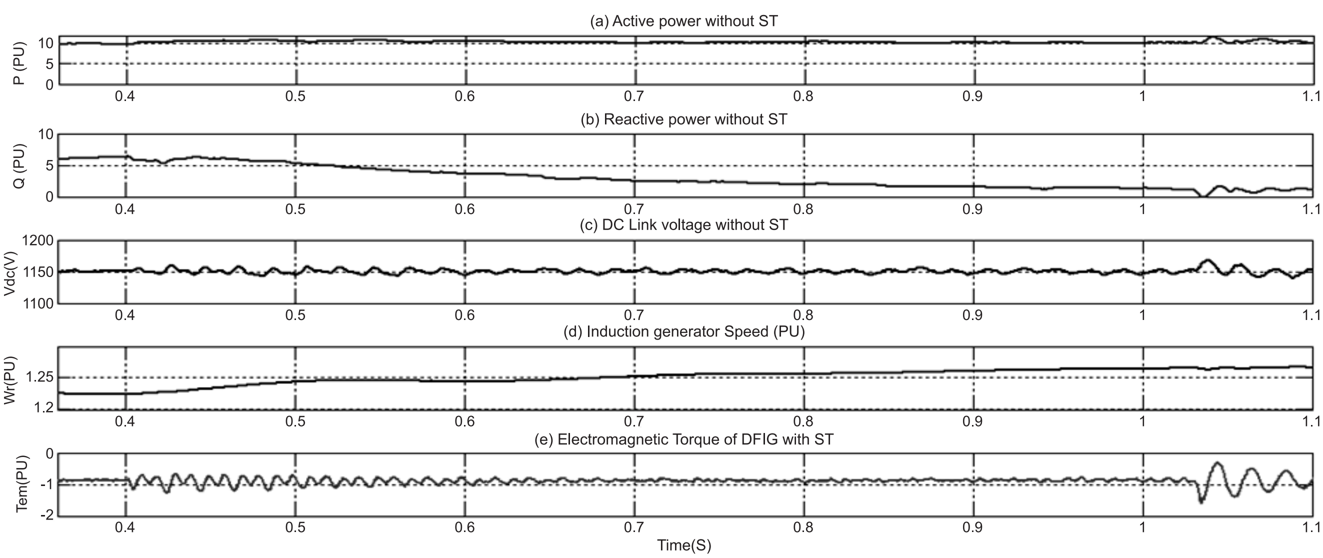


Figure 8: DFIG parameters under mitigation of voltage unbalance

Finally from Figure 5(e) and Figure 8(e) it is observed that under balanced condition almost the torque pulsation is nullified, so that the life time of DFIG is increased. The custom power devices DVR and D-STATCOM also mitigate voltage unbalance but they mitigate limited period only because of limitation of energy storage capacity [13]. Not only that the proposed ATC-ST does not have any energy storage element or any other power convertor circuit. So that the proposed ST has less cost and more effective and it mitigates voltage unbalance for unlimited period.

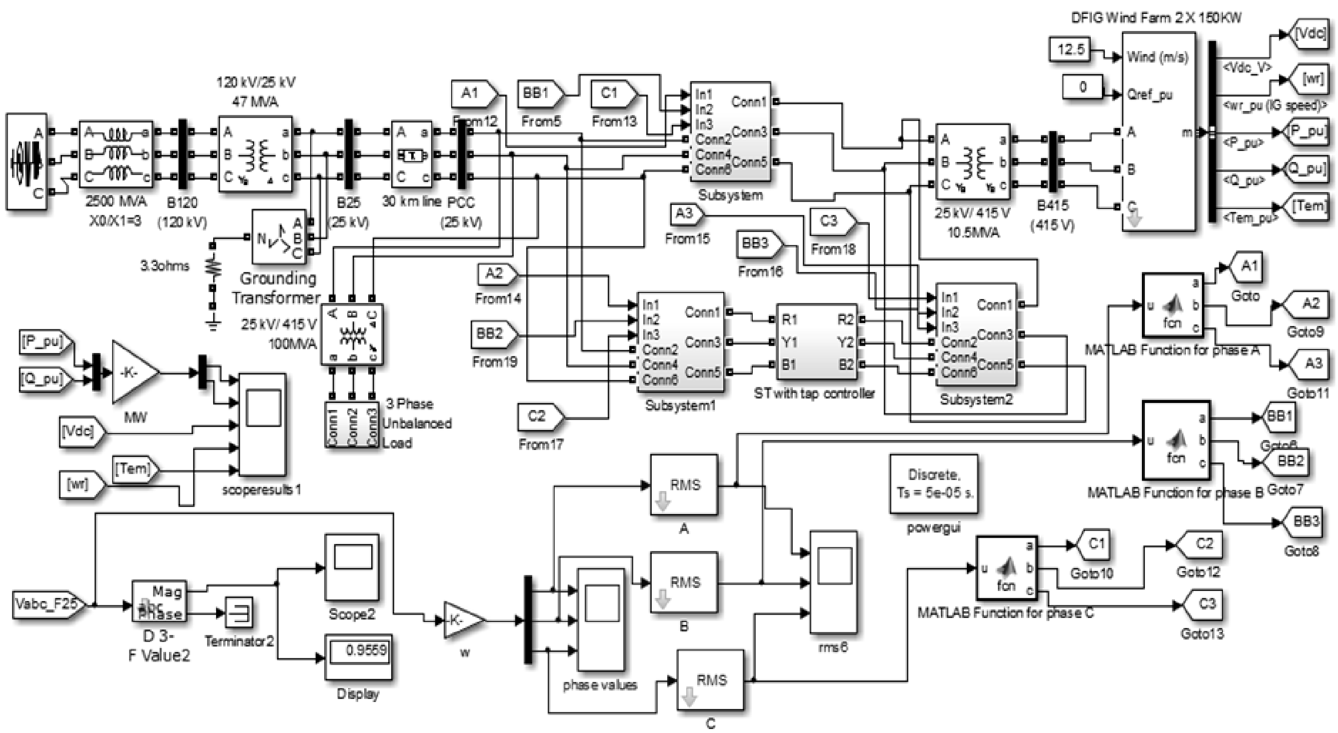


Figure 9: Grid interconnected DFIG Wind Farm with ATC-ST

5. CONCLUSION

An ATC-ST is proposed for grid interconnected DFIG wind farms to mitigate voltage unbalance. Without ATC-ST the voltage unbalance of DFIG wind farms is 19%. With ATC-ST the value is reduced to 0.4%. Compare to all other custom power devices like DVR, the proposed method has less installation cost, easy maintenance due to absence of energy storage elements and convertor circuit. The simulation results proved that ATC-ST mitigates all voltage unbalance problems of DFIG wind farms for unlimited period efficiently.

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