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Design and Operation of a Solid State Transformer in Power Distribution System

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Abstract: In recent years the complexity of the grid systems has grown due to the increased penetration of renewable energy and distributed generation sources. The increased complexity requires new methods to quickly manage the changing sources and loads. This research focuses on one of such technologies, called the Solid State Transformer (SST). In wind energy conversion systems, the fundamental frequency step-up transformer acts as a key interface between the wind turbine and the grid. Recently, there have been efforts to replace this transformer by an advanced power-electronics-based solid-state transformer (SST). This project proposes a configuration that combines the doubly fed induction generator-based wind turbine and SST operation. A SST uses power electronic devices and a high-frequency transformer to achieve isolation and voltage conversion from one level to another. Several SST topologies have been proposed by different research groups, without a clear consensus on which is most suited for grid applications. The main objective of the proposed configuration is to interface the turbine with the grid while providing enhanced operation and performance. In this project, SST controls the active power to/from the rotor side converter, thus, eliminating the grid side converter. The proposed system meets the recent grid code requirements of wind turbine operation under fault conditions. Additionally, it has the ability to supply reactive power to the grid when the wind generation is not up to its rated value. A detailed MATLAB/SIMULINK simulation study is conducted to validate the performance of the proposed configuration.

Keywords: Doubly Fed Induction Generator, Fault Ride Through, Power Electronic Transformer, Solid-State Transformer.

I. INTRODUCTION

The traditional Line Frequency Transformer (LFT) has been used since the introduction of AC systems for voltage conversion and isolation. The widespread use of this device has resulted in a cheap, efficient, reliable and mature technology and any increase in performance are marginal and come at great cost. Despite its global use, the LFT suffers from several disadvantages. Some of these are: Bulky size and heavy weight, Transformer oil can be harmful when exposed to the environment, Core saturation produces harmonics, which results in large inrush currents, Unwanted characteristics on the input side, such as voltage dips, are represented in output waveform, Harmonics in the output current has an influence on the input. Depending on the transformer connection, the harmonics can propagate to the network or lead to an increase of primary winding losses. Relative high losses at their average operation load. Transformers are usually designed with their maximum efficiency at near to full load, while transformers in a distribution environment have an average operation load of 30%. All LFTs suffer from non-perfect voltage regulation. The voltage regulation capability of a transformer is inversely proportional to its rating. At distribution level, the transformers are generally small and voltage regulation is not very good. Amongst the many technologies that exist for wind energy conversion systems (WECS), doubly fed induction generators (DFIG) have been prevalent due to variable speed operation, high power density and lower cost. DFIG based WECS consist of an induction generator whose stator is directly connected to the grid while its rotor is connected via back to back converters known as the rotor side converter (RSC) and grid side converter (GSC), respectively.

The generator is normally operated at a range of 500 V–700 V and is connected to the transmission network (11–33 kV) through a transformer that acts as an integral part of the WECS to interface the wind turbine and the grid. Recently, there has been much interest in developing an alternative to the traditional fundamental frequency transformer using solid-state devices. A new configuration is proposed that combines the operation of DFIG based WECS and SST. This configuration acts as an interface between the wind turbine and grid while eliminating the GSC of DFIG. Moreover, it is essential to have fault ride through (FRT) incorporated in DFIG system to meet the grid code requirements. In the proposed work, the developed configuration allows DFIG to ride through faults seamlessly, which is the aspect (FRT) that has not been addressed in the earlier work on SST interfaced WECS. The solid-state transformer (SST) achieves voltage conversion through a series of power electronics devices while offering multiple advantages, such as, smaller size, improved power quality and fault tolerant features.

II. SOLID STATE TRANSFORMER (SST)

The Solid State Transformer (SST) provides an alternative to the LFT as shown in Fig.1.

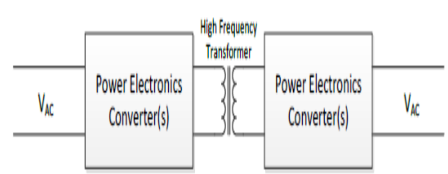


Fig.1. SST Concept.

It uses power electronics devices and a high-frequency transformer to achieve voltage conversion and isolation. It should be noted that the SST is not a 1:1 replacement of the LFT, but rather a multi-functional device, where one of its functions is transforming one AC level to another.A SST can be used instead of the conventional LFT in any electrical system, but because of its additional advantages and functions, the application of the SST in certain areas is much more attractive. Examples of these applications are:

Locomotives And Other Traction Systems: The transformer used in current locomotive vehicles is 16.7Hz and is ±15% of the total weight of the locomotive. The SST can provide a significant weight reduction. Additionally, the SST is also able to improve the efficiency, reduce EMC, harmonics and acoustic emissions.

Offshore Energy Generation: Offshore generation, whether from wind, tidal or any other source, can benefit from the reduction in weight and size. This reduction leads to smaller and thus cheaper offshore platforms. Another advantage is that the SST can achieve unity power factor, thus increasing the efficiency in power transmission.

Smart Grids: In future power systems, the usage of renewable generation is expected to increase, and will require an energy management scheme that is fundamentally different from the classic methods. For fast and efficient management of the changes in different loads and sources, the SST can be used to dynamically adjust the energy distribution in the grid. The function of the SST as described in this scenario is similar to that of a router, but instead of managing data, the SST will manage the flow of energy. For this reason, the SST is sometimes also called an energy router.

III. SYSTEM MODELING

The solid-state transformer (SST) achieves voltage conversion through a series of power electronics devices while offering multiple advantages, such as, smaller size, improved power quality and fault tolerant features. It shows a power distribution system based on SST as envisioned, advances in solid-state technology have made SST more viable today leading to increased research in its feasibility and physical realization. A promising 10 kVA prototype has been developed and presented. Further, the use of high voltage silicon carbide (SiC) power devices for SST has been explored and presented. As seen in SST can act as an interface between the grid and generation sources. However, research showing detailed configurations for integrating existing technologies is limited. In work is reported on using SST in a microgrid based on renewable sources. In SST is used to interface a wind park based on squirrel cage induction generator (SCIG) with the grid. However, a detailed analysis on fault ride through requirement and reactive power support has not been conducted. It has been reported that a DFIG based wind turbine is the lightest amongst the current wind systems which also explains its wide commercial use. Moreover, in the proposed configuration, the GSC present in traditional DFIG systems is removed making the machine setup further lighter. On the other hand, SST being used in an AC/AC system is expected to be 25% smaller in volume than traditional low frequency transformer. Thus, the use of SST to interface a DFIG based wind system can be expected to provide further reduction in weight and volume when compared to other wind systems with the fundamental frequency transformer.

The general DFIG based WECS representation is shown in Fig. 2(a) whereas the proposed system configuration is shown in Fig. 2(b). In the proposed configuration, the fundamental frequency transformer is replaced by the SST. The proper control of SST converter that is close to the stator of DFIG, addressed as machine interfacing converter (MIC), can aid the machine in its operation. Thus, it is proposed to eliminate the GSC in the DFIG system configuration by incorporating its role in SST. Note that this new arrangement modifies the overall operation and control of standard GSC-RSC based DFIG system. In principle, the machine terminal voltages can be maintained constant in spite of any voltage variations in the grid using MIC. The direction of power flow in the proposed configuration occurs from the low voltage machine terminals to the grid. The MIC is responsible for: (i) maintaining the required voltages at the stator terminals and (ii) transferring the real power from the stator terminals (Ps) to the low voltage DC bus (vldc). This low voltage DC bus is regulated by the high frequency stage converters (HB1 and HB2) and not by the DFIG. In other words, MIC acts as a stiff grid at the stator terminals. Interestingly, the low voltage DC bus (magnitude) is very close to the one controlled by GSC in the regular DFIG configuration [vldc1 in Fig. 2(a)]. This allows the RSC in the proposed configuration to be connected directly to vldc of SST. The vldc has two functions, namely, (i) to transfer active power from the stator terminals to the grid and (ii) to transfer active power (Pr) to/from the RSC during sub-synchronous or super-synchronous operation.

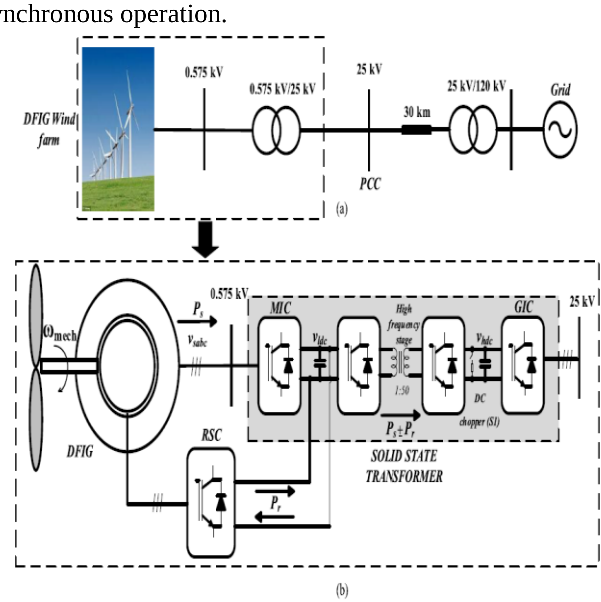


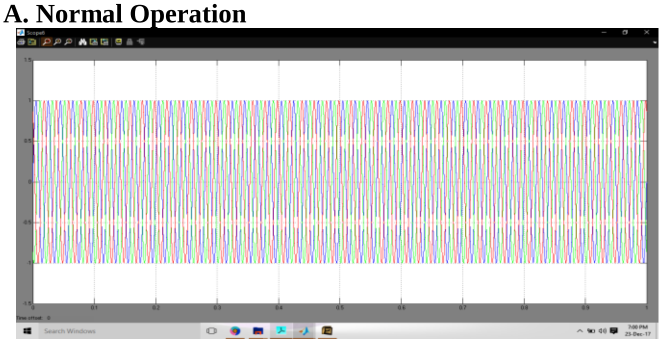
Fig.2. (a) Regular DFIG configuration and (b) Proposed SST based DFIG configuration.

The power transfer through the high frequency stage, from the low voltage DC bus to the high voltage DC bus (vhdc), is controlled by introducing a phase shift between the two high frequency AC voltages with the objective of regulating the DC bus voltage (vldc). The grid interfacing converter (GIC) connects SST to the grid and maintains the DC link (vhdc) by exchanging active power with the grid. To provide an effective FRT in the proposed configuration, a DC chopper is incorporated at vhdc bus. During the grid fault conditions, the power being generated by the wind turbine is evacuated through the high frequency stage into the DC chopper. Further, the high frequency stage continues to maintain the low voltage DC bus (vldc), allowing the voltages at the machine terminals to be constant. The presence of GIC further helps to achieve the recent grid code requirements of reactive current injection without requiring any additional control or device. Furthermore, the GIC can provide reactive power support to the grid during low wind generation periods.

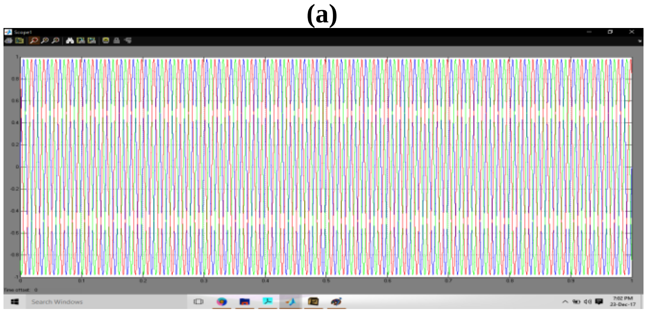
IV. SIMULATION RESULTS

To verify the effectiveness of the proposed configuration, detailed simulations are carried out. A detailed model of proposed configuration is developed using the SIMULINK and Sim Power Systems toolbox in MATLAB.

A. Normal Operation



(a)



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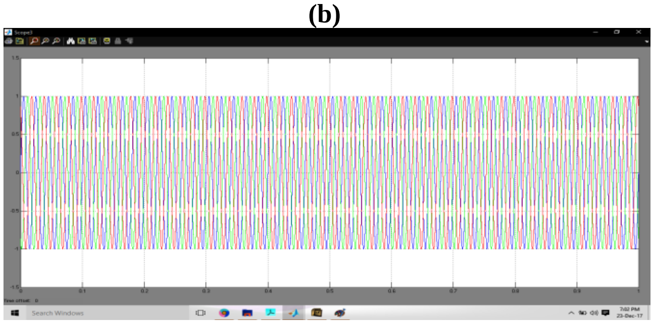

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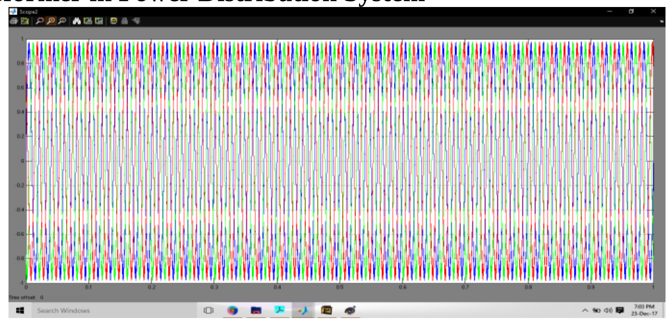

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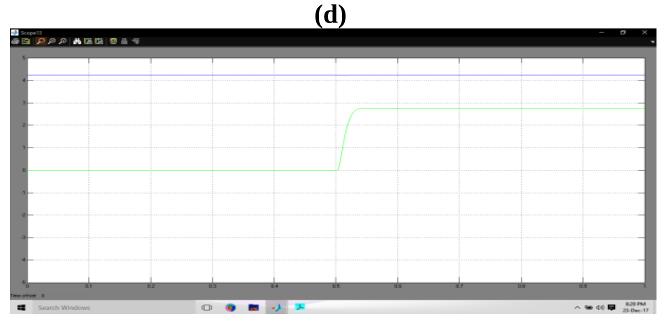
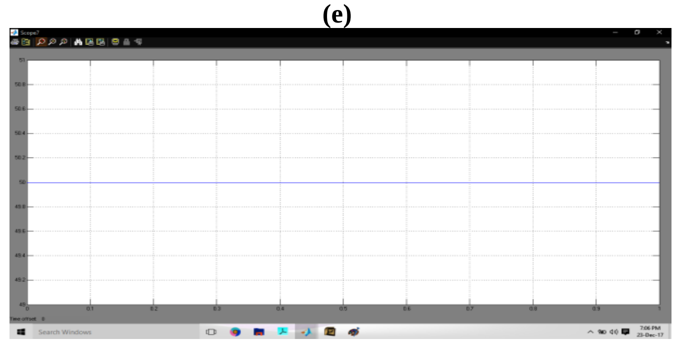
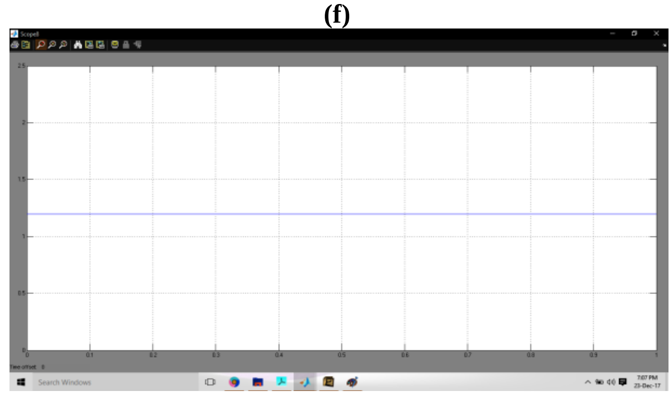


(e)



(f)



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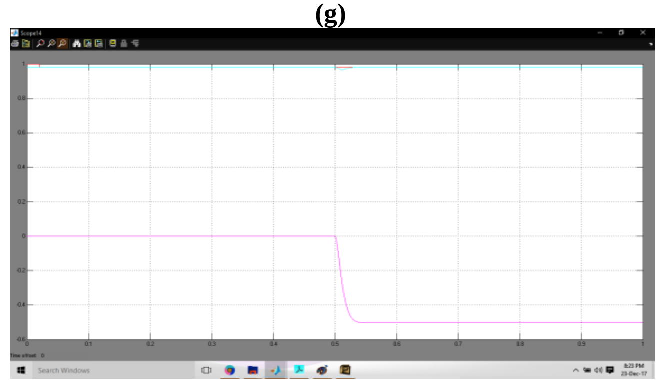

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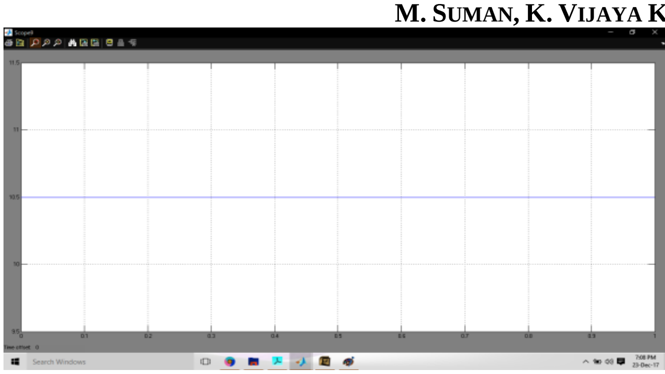


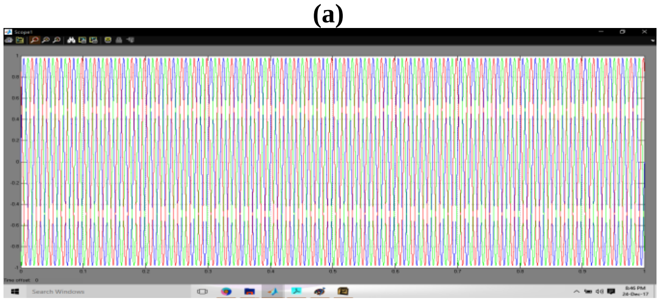
(i)

Fig.3. Normal operation of proposed configuration showing dynamics of P and Q injection. (a) Grid voltages, (b) grid currents,(c) stator terminal voltages, (d) stator currents, (e) active and reactive power injected by the system, (f) high voltage DC bus voltage, (g) low voltage DC bus voltage,(h) inner loop controlled axis grid currents and (i) rotor speed.

Firstly, the operation of the proposed configuration is shown under normal grid conditions in Fig. 3. In this scenario (between 4.9 to 5 sec), the wind turbine is operated at a speed of 13 m/s thus not producing peak power. The wind turbines produce a total of 4.2 MW active power. Like general DFIG, the system delivers this wind generated active power to the grid as shown in Fig. 3(e) through the SST. That is, there is no reactive power support from the GIC. Figs. 3(a) and (b) show the grid voltages and currents at the output of the GIC. Figs. 3(c) and (d) give the stator terminal voltages and machine currents at 0.575 kV. The high and low voltage DC bus voltage profiles are illustrated in Figs.3(f) and (g), respectively. Fig. 3(h) provides the controlled inner loop d-axis and q-axis currents of the GIC that control the active and reactive power injection into the grid, respectively. Fig. 3(i) shows the rotor speed of the machine which remains constant at 1.2 p.u.

B. Symmetrical Fault

(a)



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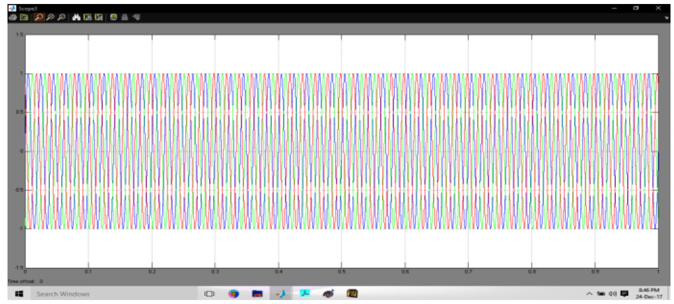

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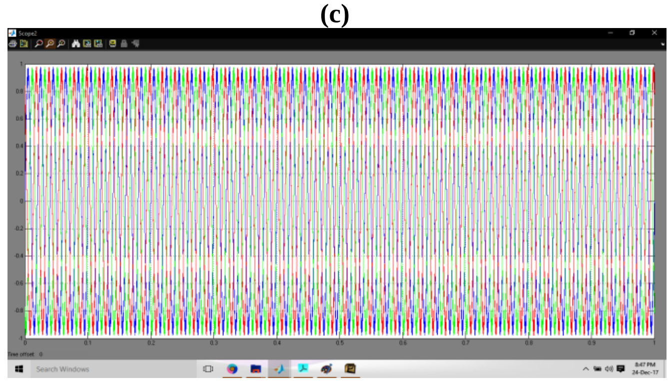

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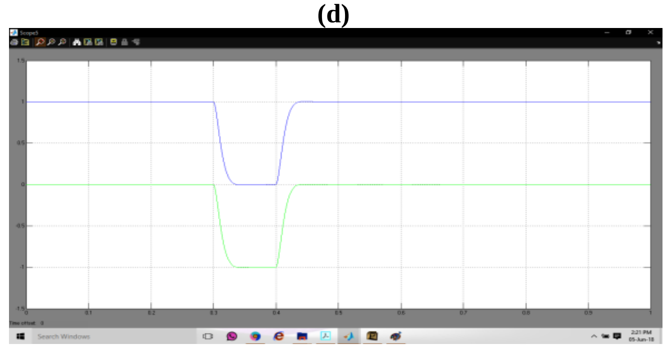

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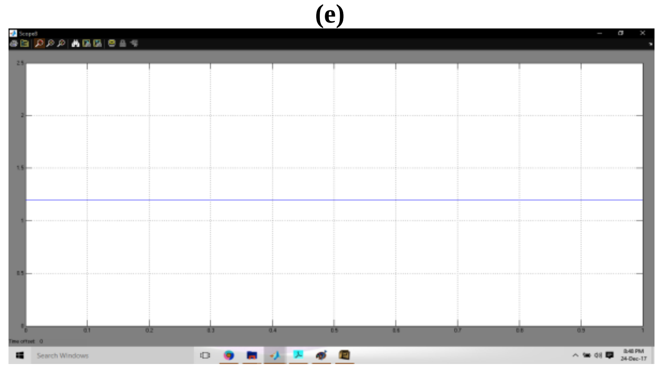

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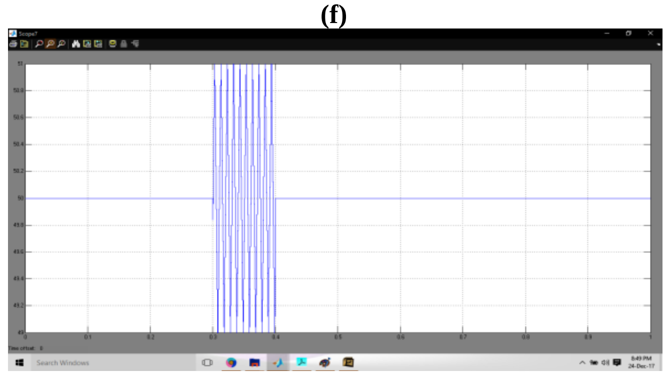

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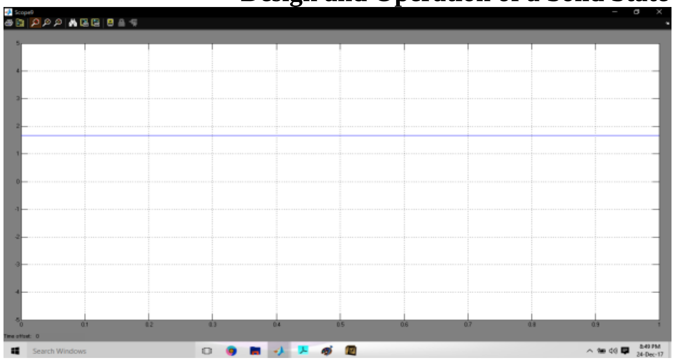
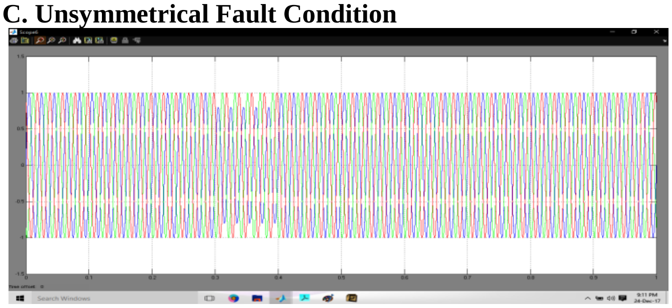


(h)

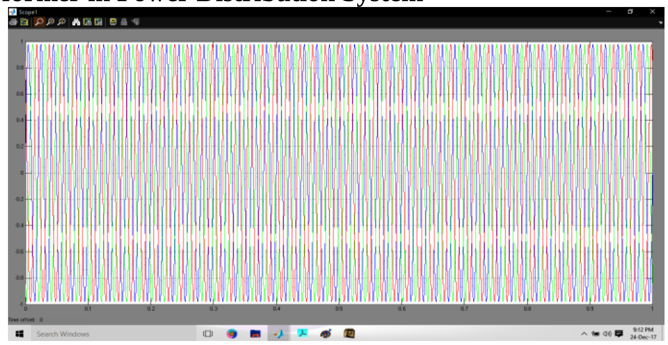
Fig.4. Performance of the proposed configuration under three-phase symmetrical LLL-G fault. (a) Grid voltages, (b) grid currents, (c) stator terminal voltages, (d) stator currents, (e) inner loop controlled axis grid currents, (f) low voltage DC bus (g) high voltage DC bus voltage and (h) rotor speed.

The performance of proposed configuration to meet FRT requirements in recent grid codes are discussed in this section. A severe LLL-G fault is applied at upstream grid when the DFIG is producing maximum power (at 15m/s). The results are shown in Fig. 4. The fault is detected by sensing the positive sequence voltage magnitude. Fig. 4(a) shows the grid voltages during the fault which is introduced at 3 sec and lasts for 150 ms as per the grid code requirement. Fig. 4(b) shows the grid currents injected by the GIC. Figs.4(c) and (d) depict the stator voltage and currents of the machine, respectively. Note that the turbine does not see any change in the operating condition as MIC maintains the rated stator voltages despite the severe fault condition. Fig. 4(f) shows the low voltage DC bus which remains constant. Further, as seen from Fig. 4(g), the DC chopper evacuates the active power generated by the turbines successfully. Thus, in the proposed configuration, turbines seamlessly ride through the grid fault. On the grid side, the GIC is controlled to inject necessary reactive current to meet the grid codes. Fig. 4(e) shows the d and q-axis currents of the GIC, igd and igq, respectively. In pre-fault conditions it can be seen that igd is at 1 p.u. since the wind turbine is operated at maximum capacity. The q-axis current igq on the other hand is at zero as no reactive power is being injected. At 3 sec, when the fault occurs, the fault switch (FS2) is set to position 2 and the reactive current reference i*gq is calculated. The GIC, thus, injects 0.9 p.u. reactive current that can be seen in Fig. 4(e).

C. Unsymmetrical Fault Condition



(a)



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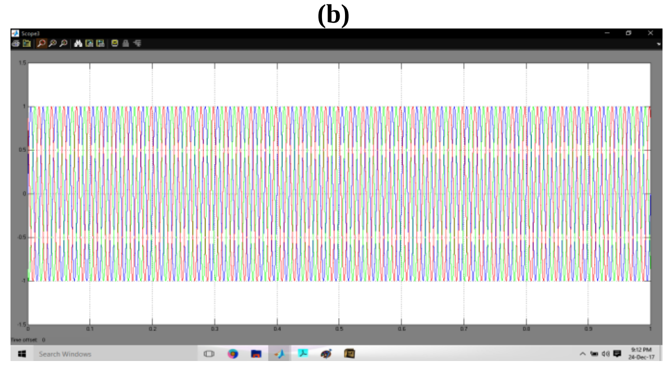

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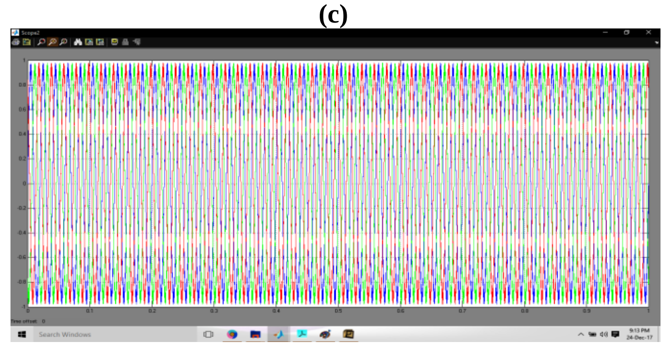

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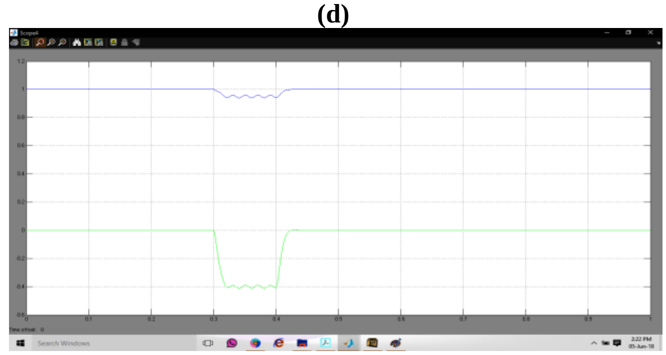

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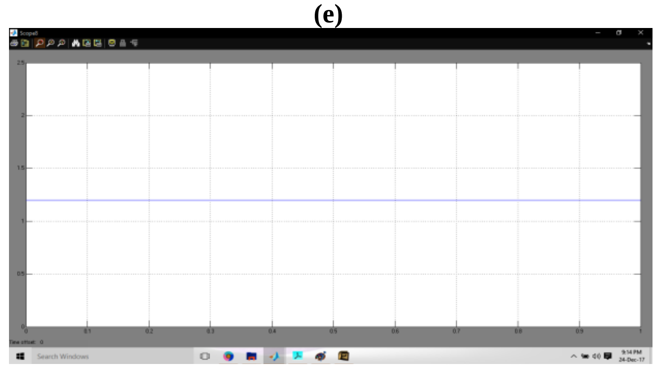
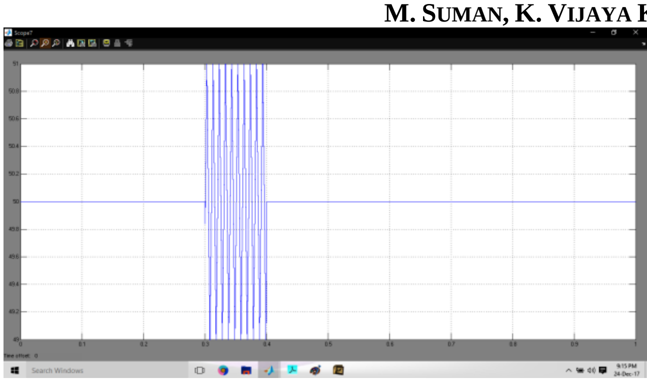


(f)



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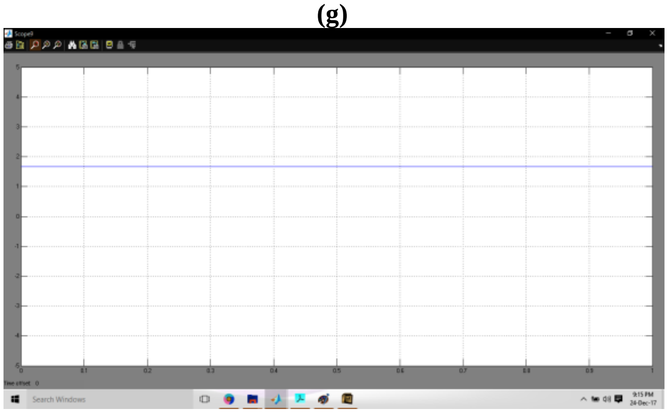

(h)

Fig.5. Performance of the proposed configuration under three-phase unsymmetrical L-G fault. (a) Grid voltages, (b) grid currents,(c) stator terminal voltages, (d) stator currents, (e) inner loop controlled axis grid currents, (f) low voltage DC bus (g) high voltage DC bus voltage and (h) rotor speed.

The performance of the proposed configuration is tested under unsymmetrical faults condition as well. A single phase L-G fault is applied at the upstream grid when the DFIG is producing maximum power (15m/s). Fig. 5(a) shows the grid voltages when the fault occurs at 3 sec and lasts for 150 ms. Fig. 5(b) shows the grid currents injected by the GIC. Note that the currents remain symmetrical despite the unsymmetrical fault. Figs.5(c) and(d) show the stator voltages and currents which remain undisturbed as the MIC maintains rated stator voltages similar to the symmetrical case. Fig. 5(f) shows the low voltage DC bus. Fig. 5(g) shows the chopped DC bus voltage. Note that during a single phase fault, active power is still being transferred to the grid and the amount of power evacuated through the DC chopper is lesser than the case of a severe three phase fault. During this fault, the positive sequence voltage drops to 0.8 p.u. giving the reactive reference current (i*gq) as 0.4 p.u. The reactive d and q axis currents, igd and igq are shown in Fig. 5(e), respectively.

V. CONCLUSION

In this project, a new system configuration that combines DFIG and SST operation has been proposed. This configuration replaces the regular fundamental frequency transformer with advanced power electronics based SST. The key features of the proposed configuration are outlined below:

- Replacement of regular fundamental frequency transformer with SST leading to smaller footprint.
- Direct interface with SST to inject active power.
- Elimination of GSC in a standard DFIG system as the active power to/from RSC is regulated by MIC.
- Simplified DFIG control as machine supports only active power. The reactive power is supported by GIC during both normal and fault conditions.
- Seamless fault ride through operation during both symmetrical and unsymmetrical faults as per the latest grid codes.

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