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Dynamic Performance of DFIG using SMES For WECS

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***Abstract*— The integration of wind turbines into modern power grids has significantly increased during the last decade. Wind turbines equipped with doubly fed induction generators (DFIGs) have been dominating wind power installation worldwide since 2002. In this project work, superconducting magnetic energy storage (SMES) unit is being used to improve the dynamic performance of a wind energy conversion system equipped with DFIG during voltage sag and voltage swell at the grid side.The converter and the chopper are controlled using a hysteresis current controller (HCC) and a fuzzy logic controller (FLC) respectively. The basic implementation of the HCC is based on deriving the switching signals from the comparison of the actual phase current with a fixed tolerance band around the reference current associated with that phase. To control power transfer between the SMES coil and the ac system, a dc–dc chopper is used, and fuzzy logic is selected to control its duty cycle (D) with input variables real power generated by the DFIG and the SMES coil current.The MATLAB/SIMULINK software is used to simulate the wind turbine, the SMES unit, and the model under study. Results are to be analyzed to highlight the improved dynamic performance of wind energy conversion systems in conjunction with the SMES unit. Detailed simulation is to be carried out using MATLAB/SIMULINK software to highlight the impact of the SMES unit in improving the overall system performance under voltage sag and voltage swell conditions.**

***Keywords*—Doubly fed induction generator (DFIG), fuzzy logic, hysteresis current controller (HCC), superconducting magnetic energy storage (SMES), voltage sag, voltage swell and wind energy conversion system (WECS).**

I. INTRODUCTION

Energy is essential to everyone no matter when and where they are. This is especially true in this new century, where people keep pursuing for better quality of life. Among different types of energy, electrical energy is one of the most important that people need everyday. It is now a globally accepted reality that electrical energy is fundamental for social and economic development. Unfortunately still one-third of the world's total population live in developing and threshold countries and have no access to electricity. It has been estimated that the world's population will reach eight billion by 2020.

The statistics show that the population growth is mostly in developing countries where most of the people live in remote and rural areas.

So, to supply electricity to them, extension of grid is necessary but it is very complicated and expensive process due to geographical, economical and social barriers. Up to now, many diesel generator sets are used for rural electrification which is not a good solution since the fuel's maintenance cost is high and moreover it is not environment friendly.

In such circumstances, the best alternative is to use locally available renewable energy sources such as Photovoltaic, wind, hydrogen, etc.., and to implement them as modular, expandable and task-oriented systems that guarantee cost-effective and sustainable resources of energy, especially for remote and rural areas. At the World Engineering Convention in 2000, it has been mentioned that "the energy needed will be provided, distributed and consumed in a suitable way". Keeping that promise in mind, many available renewable energy sources are integrated into power grids. Multi-source alternative energy systems with proper control have great potential to provide higher quality and more reliable power to customers than a system based on a single resource.

Wind turbine generators operate at variable-speed. Earlier wind energy conversion systems are based on generator directly connected to the grid; hence the speed of the system was constant. The evolution of power semiconductors has contributed enormously to variable speed energy conversion systems by interfacing the constant frequency of the grid to the variable frequency of the generator. Variable-speed operation of wind turbines demands the application of variable-speed generators operating on the constant frequency of the grid. For such an operation all the generators require the use of suitable electronic power converter.

The Doubly Fed Induction Generator (DFIG) is one of the most popular variable-speed wind turbine generators (WTG). DFIG is an electrical machine in which variable-speed operation is provided by using a relatively small power electronic converter to control currents in the rotor, such that the rotor does not necessarily rotate at the synchronous speed of the magnetic field set up in the stator.

In this technology, the rotor winding is connected to a coupling transformer through a back-to-back partial scale Voltage Source Converter (VSC), whereas the stator winding is directly connected to the grid at a point of common coupling (PCC) through the coupling transformer.

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The voltage source converter decouples the mechanical and electrical frequencies and makes variable-speed operation possible. In DFIG the windings present on both stationary and rotating parts transfer significant power between shaft and the electrical system. DFIG is very sensitive to faults that occur on the grid side.

In this project, a Superconducting Magnetic Energy Storage (SMES) unit is connected to the wind turbine equipped with DFIG during voltage sag and voltage swell at the grid side to improve the performance of DFIG. SMES unit stores energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to temperature below its superconducting critical temperature. A typical SMES system includes three parts i.e. superconducting coil, power conditioning system and cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. SMES coil discharges during the voltage sag event so as to compensate its stored energy for the decrease in voltage and charges during the voltage swell so as to absorb the energy because of the increase in voltage. SMES systems are highly efficient and its efficiency is greater than 95% and hence it is preferred over other energy storage devices. The SMES configuration presented in this paper consists of a Voltage Source Converter (VSC) and dc-dc chopper. The converter and chopper are controlled using Hysteresis Current Controller (HCC) and Fuzzy Logic Controller (FLC) respectively. SMES unit has many potent applications in power systems and energy systems. These control techniques along with new application of SMES unit are employed in this project to improve transient response of WTG equipped with DFIG during faults.

II. DFIG

Wind turbines equipped with Doubly Fed Induction Generator (DFIG) have been used in this project. DFIG is one of the most popular variable speed wind turbine generator. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings.

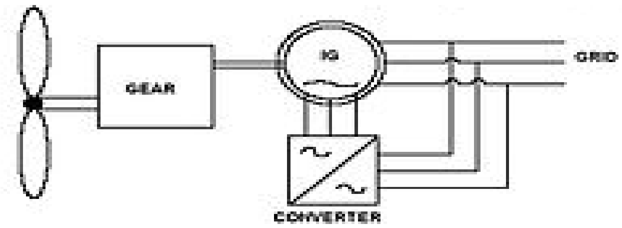
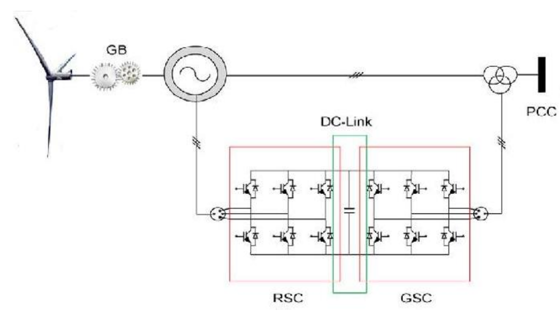


Fig. 1. Principle of DFIG connected to a wind turbine

The principle of the DFIG is that the rotor windings are connected to the grid via slip rings and back-to-back Voltage Source Converter (VSC) that controls both the rotor and grid currents. Thus, rotor frequency can differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control, which has better stability when high reactive currents are required from the generator.

A. Typical configuration of individual DFIG



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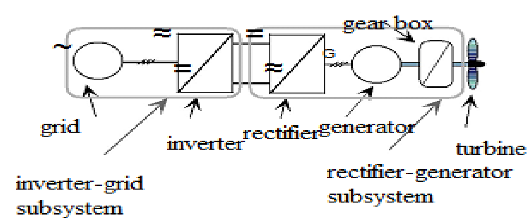

(b)

Fig.2. (a) Typical configuration of individual DFIG. (b) Overview of the electrical system for variable-speed system

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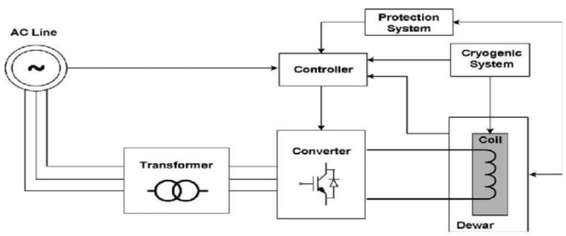
The Fig.2 (a) shows the typical configuration of an individual DFIG. The wind energy is applied to a turbine which converts kinetic energy from the wind into mechanical energy. The power from the rotation of the wind turbine rotor is transferred to the generator through the power train, i.e. through the main shaft, the gear box and the high speed shaft. A Gear Box (GB) is used to convert slowly rotating, high torque power which comes from the wind turbine rotor to high speed, low torque power which can be used by the generator.

B. Overview of the electrical system for variable-speed system

A variable-speed electrical system has three main components. They are the generator, the rectifier and the inverter, shown in Fig. 2 (b) The system can be split into two subsystems: inverter-grid and rectifier-generator. This helps when analyzing one part of the system. Each sub-system has at least two different device alternatives.

The induction generator requires reactive power to operate. Consequently, the IG often uses the VSC, which produces reactive power. Another possibility is to use a diode rectifier or a thyristor rectifier together with capacitors, which produce the required reactive power. Unfortunately, reactive power changes with speed and if the capacitance value is not correct, the performance of the system will be low. The inverter of the system is connected to the grid. Here, the grid-commutated inverter, also called the thyristor inverter, and the VSC can be used. The VSC requires a minimum dc-link voltage in order to operate, and in some cases a step-up converter (DC/DC) must be introduced to increase the voltage level for the VSC. The VSC can act both as a rectifier and as an inverter: the power direction is set by the controller. Depending on the optimization of the rectifier-generator subsystem, the rated power can be increased by 50 % when using a VSC, instead of a diode rectifier or a thyristor inverter.

III. SMES



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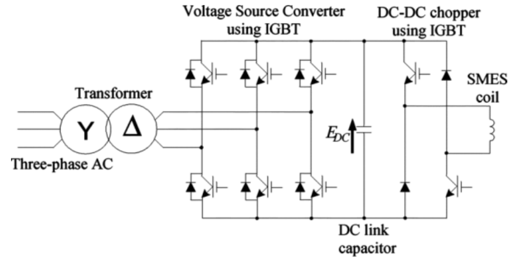

(b)

Fig.3 (a) Typical schematic diagram of an SMES unit. (b) Basic configuration of VSC-based SMES system

An SMES unit consists of a large superconducting coil at cryogenic temperature. This temperature is maintained by a cryostat or Dewar that contains helium or nitrogen liquid vessels. A bypass switch is used to reduce energy losses when the coil is on standby. And also it serves other purposes such as by-passing dc coil current if utility tie is lost, removing converter from service, or protecting the coil if cooling is lost. A typical schematic diagram of an SMES unit is shown in Fig.3 (a).

The stored energy in the SMES coil is given by

$$E = \frac{1}{2} I_{SMES}^{2} L_{SMES} \quad (1)$$

where E = stored energy of the SMES unit

I_{SMES} = current in the SMES coil

L_{SMES} = inductance of the SMES coil

Generally, there are two major configurations of SMES i.e. CSC and VSC. Both CSC and VSC can allow independent control of the real and reactive power flowing between the superconducting coil and the power system network. Traditionally, CSC is connected through a 12-pulse converter configuration to eliminate the ac-side fifth and seventh harmonic currents and the dc-side sixth harmonic voltages, thus resulting\g in significant savings in harmonic filters. However, because this configuration uses two 6-pulse CSCs that are connected in parallel, its cost is relatively high. Moreover, CSC topology is meant to supply high level of capacitive reactive power and also CSC-based SMES is dependent of coil in providing VAR support.

VSC-based SMES is used in this project as it is connected with dc-dc chopper through a dc link, which facilitates energy exchange between the SMES coil and the ac grid.

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The total cost of switching devices of the CSC is estimated to be 173% of the switching devices of power diodes required for equivalent capacity of the VSC and the chopper. Moreover, a VSC has better self-commutating capability, and it injects lower order harmonic currents into ac grid than a comparable CSC. Also, VSC-based SMES can provide continuous rated capacity VAR support even at low or no coil current. The use of IGBTs in this configuration is more beneficial than GTO since the switching frequency of an IGBT lies in the range of 2-20 kHz, whereas, in case of GTO, the switching frequency cannot exceed 1 kHz.

IV. SMES CONTROL APPROACHES

VSC provides a power electronic interface between ac power system and the superconducting coil. The converter and the chopper are controlled using hysteresis current controller and fuzzy logic controller respectively. In the past, control system of the dc-dc chopper is presented but control approach of VSC as part of SMES configuration was not presented. Also the SMES coil is proposed to be connected to individual DFIG's converters making it appropriate only for new wind turbine installations.

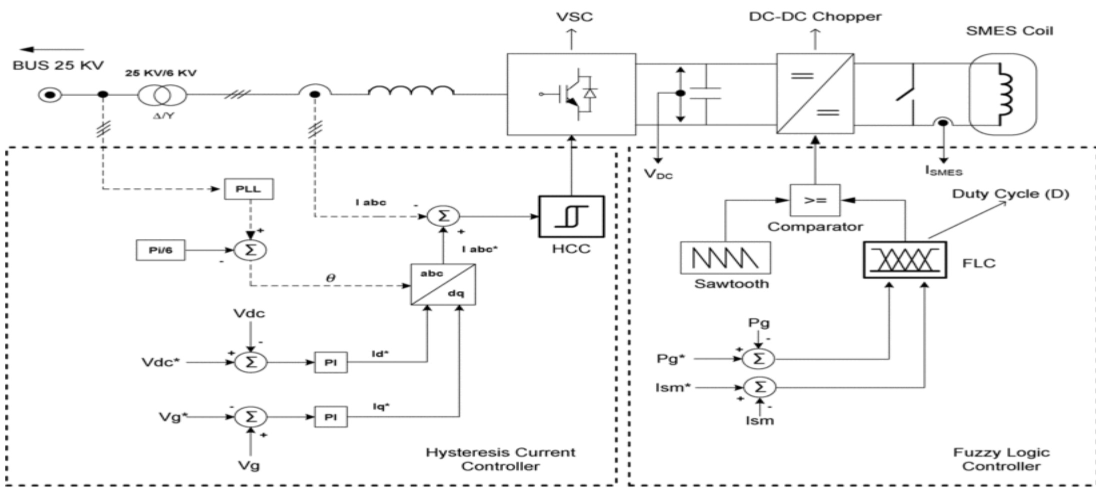

Fig.4 SMES unit configuration and the proposed HCC-FLC control scheme

Also SMES unit is applied to microgrids so as to stabilize entire microgrid systems. The control scheme employed for the SMES unit in microgrid is very complex and requires robust computational system. The control algorithm used in this project is much simpler and closer to realistic applications. The control scheme used in this project comprises of only two Proportional Integral (PI) controllers and considers SMES coil current to take the SMEs stored energy capacity into account, along with the DFIG generated power as control parameters to determine the direction and level of power exchange between the SMEs coil and the ac system unlike the older control scheme employing four PI controllers which require more computational time to optimally tune its parameters to maintain overall system stability and to achieve satisfactory dynamic response durong transient events. The presently used control system is simple, efficient and easy to implement.

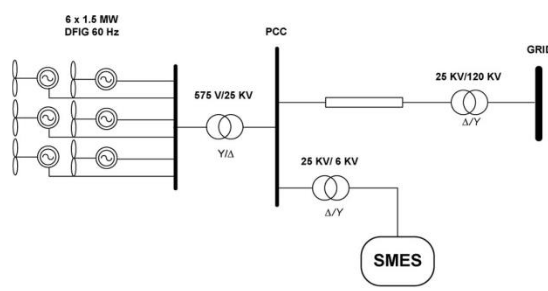

Fig.5 System under study with SMES unit

A. Hysteresis Current Controller (HCC)

The current control methods play an important role in power electronic circuits, particularly in current regulatede PWM inverters which are widely applied in ac motor drives and continuous ac supplies where the objective is to produce sinusoidal ac output.

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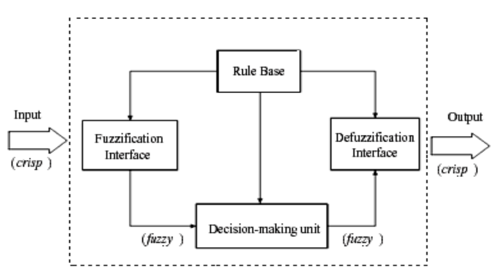
Nevertheless, due to lack of coordination among individual HCC's of three phases, high switching frequency may happen, and the current error is not strictly limited The actual current waveform is not only determined by the hysteresis control: depending on operating conditions, the current slope may vary widely and the current peaks may appreciably exceed the limits of the hysteresis band.

The Fig.4 shows proposed SMES with an auxillary PLL controller. The PI controllers determine the reference d- and q-axis currents by using the difference between the dc link voltage V_{dc} and reference value V_{dc}^*, and thediffernce between terminal (grid) voltage V_g and reference value V_g^*, respectively. The HCC signal is generated for IGBT switching and the HCC compares the three-phase line currents (I_{abc}) with the reference currents (I_{abc}^*), which is dictated by the I_d^* and I_q^* references. The value of I_d^* and I_q^* is converted through Park transformation (dq0-abc) to produce reference current (I_{abc}^*). The dc voltage across the capacitor is kept constant throughout by the converter.

B. Fuzzy Logic Control (FLC)

To control power transfer between the SMES coil and the ac system, a dc-dc chopper is used, and fuzzy logic is selected to control the duty cycle (D). The superconducting coil is charged or discharged by a two-quadrant dc-dc chopper. The dc-dc chopper is controlled to supply positive (IGBT is turned on) or negative (IGBT is turned off) voltage to SMES coil and then the stored energy can be charged or discharged. Therefore, the superconducting coil is charged or discharged by adjusting the average voltage across the coil which is determined by the duty cycle of the two-quadrant dc-dc chopper. When the duty cycle is larger than 0.5 or less than 0.5, the stored energy of the coil is either charging or discharging.



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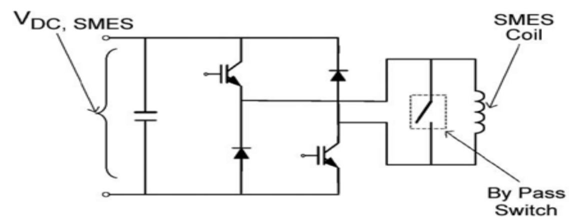

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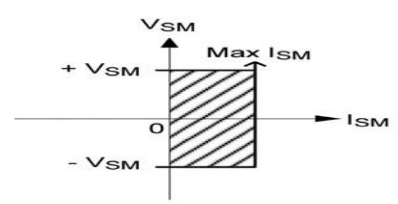
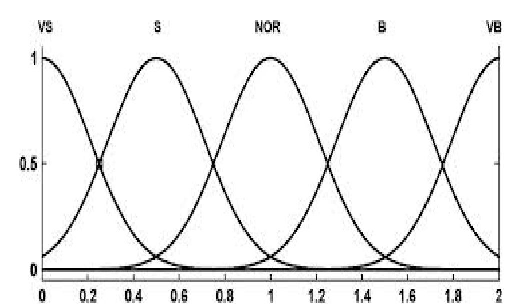


(c)

Fig.6 (a) Structure of proposed fuzzy controller. (b) Class-D dc-dc chopper using an SMES coil. (c)Operation range of SMES coil

TABLE I
PARAMETERS OF THE DFIG

Duty Cycle (D)	SMES Coil Action
D = 0.5	Standby condition
$0 \leq D < 0.5$	Discharging condition
$0.5 < D \leq 1$	Charging condition



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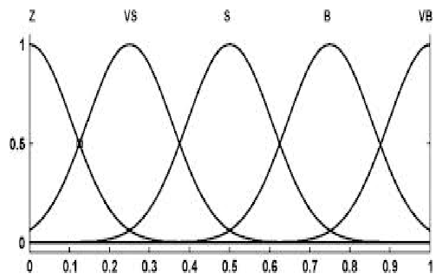

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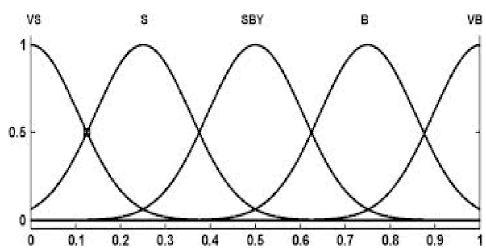


(c)

Fig.7 (a) MF for the input variable P_G (pu) (b) MF for the input variable I_{SMES} (pu) (c) MF for the output variable D

The relation between V_{SMES} and $V_{DC,\ SMES}$ is given by

$$V_{SMES} = (1-2D)\ V_{DC,\ SMES} \tag{2}$$

where V_{SMES} = average voltage across SMES coil

D = Duty cycle

$V_{DC,\ SMES}$ = average voltage across the dc-link capacitor of the SMES

The Fig.7 (a) refers to MF of active power generated by DFIG and is treated as one of the input. This MF curve has to be developed in MATLAB by making use of fuzzy command window. The Fig.7 (b) refers to MF of SMES coil current which is considered as another input which is to be given to fuzzy logic controller. This MF curve has to be developed in MATLAB by making use of fuzzy command window. All the MF's of all the variables are considered to develop all the MF's of output variable. The Fig.7 (c) corresponds to MF of output variable i.e. duty cycle (D) which is the output of fuzzy logic controller which determines the direction and the magnitude of power exchange between the SMES coil and the ac system.

The Gaussian curve is a function of a vector x and depends on parameters σ and c, which is given by

$$f\ (x;\ \sigma,\ c) = e^{-(x-c)^2/2\sigma^2} \tag{3}$$

Where σ and c are the variables that determine the center of the peak and the width of the Bell curve, respectively.

Center of gravity, which is widely used in fuzzy models, is used for the defuzzification process, where the desired output

$$z_0 = \frac{\int z.\mu_c(z)dz}{\int \mu_c(z)dz}$$

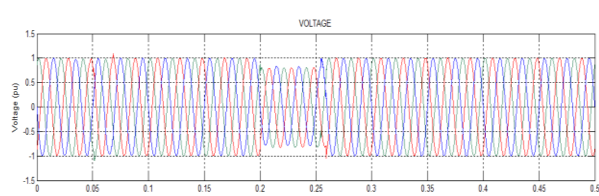
V. Simulation Results And Discussion

A. Voltage Sag Event

The simulation model consists of six 1.5 MW DFIGs connected to ac grid at the PCC. The DFIG consists of an induction generator with stator winding connected directly to the grid through a Wye-Delta step-up transformer whereas the rotor winding is connected to bidirectional back-to-back insulated gate bipolar transistor VSC. The grid is represented by an ideal three-phase voltage source of constant frequency, which is connected to wind turbine via a 30-km transmission line and Delta-Wye step-up transformer. A fault is created in the above mentioned system and the performance of the system is analyzed.

A voltage sag lasting for 0.05 secs is applied at t = 0.2 secs at the grid side. In this simulation, voltage sag is created by switching off large inductive load(4). The results thus obtained are shown in the next pages. Because of voltage sag, the normal operation is affected only during the interval of fault. Once the fault is cleared, normal operation is restored.

Due to voltage sag disturbance at the grid side, discharging mode will take place. In this case, the value of D lies in the range of 0-0.5. When voltage sag occurs, the energy stored in the coil is being delivered to AC system during this mode. The coil will be recharged at t = 0.25 secs exactly at the time when fault is cleared according to the rules of designated fuzzy logic controller for real power generated by DFIG and the SMES coil current.



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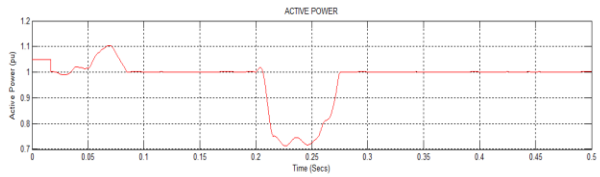

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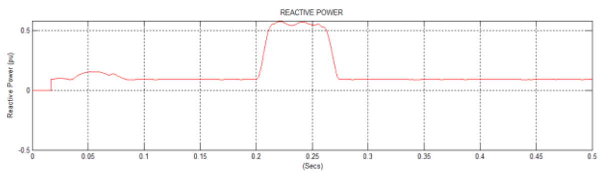


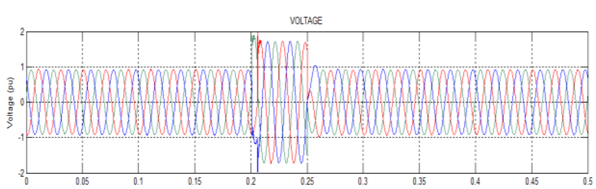
(c)

Fig. 8 (a) voltage sag (b) Active power (c) reactive power

B. Voltage Swell Event

Swell event at the grid side is rarely to occur. But if it occurs, it causes the voltage rise at the PCC that may violate grid code requirements. As swell refers to increase in voltage, this increase in voltage leads to increase in power. The voltage increase should be within the grid codes so that the wind turbine generators need not be disconnected from the grid.

A voltage swell lasting for 0.05 secs is applied at t = 0.2 secs at the grid side. In this simulation, voltage swell is applied by switching on a large capacitive bank. The results thus obtained are shown in the next pages.Due to occurrence of voltage swell disturbance at the grid side, charging mode will take place. In this case, the value of D lies in the range of 0.5 – 1. When voltage swell occurs at t = 0.2 secs, the energy is transferred from the AC system into the SMES coil as designated by fuzzy set of rules. After the fault is cleared at t = 0.25 secs, normal operation is restored.



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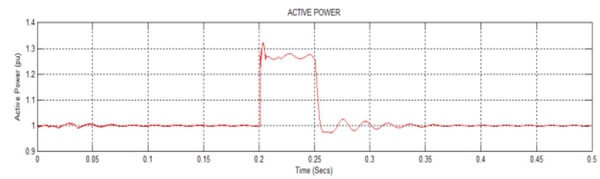

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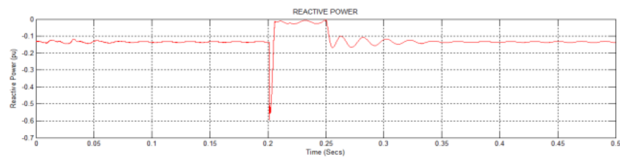

(c)

Fig. 9 (a) Voltae swell. (b) Active power. (c) Reactive power

Table II
Parameters Of The Smes Unit

Rated Energy	1.0 MJ
L_{SMES}	0.5 H
I_{SMES}	2000 A

VI. CONCLUSION

A new control algorithm along with a new application of the SMES unit to improve the transient response of WTGs equipped with DIFG during voltage sag and voltage swell events has been proposed. Simulation results have shown that the SMES unit is very effective in improving the dynamic performance of a power system with wind turbine equipped with DFIG during voltage sag and voltage swell at the grid side. The proposed control algorithm of the SMES unit is simple and easy to implement and is able to improve the FRT of the DFIG. The SMES unit, on the other hand is still a costly piece of equipment; however, due to the development of hightemperature superconducting materials, its application in power systems is expected to become viable in the near future.

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VII. AUTHOR'S PROFILE:

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