DFIG PERFORMANCE IMPROVEMENT DURING FIRE-THROUGH FAULT WITHIN ROTOR SIDE CONVERTER SWITCHES

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ABSTRACT
Doubly Fed Induction Generators (DFIGs) are currently widely used in variable speed wind power plants due to their superior advantages that include reduced converter rating, low cost, reduced losses, easy implementation of power factor correction schemes, variable speed operation and four quadrants active and reactive power control capabilities. DFIG is interfaced to the ac network through the grid-side voltage source converter (GSC) and rotor-side RSC to enable the variable-speed operation of the wind turbine and to provide reactive power support to the ac grid during disturbance events. Converter switching malfunction such as fire-through may influence the power dispatch capability of the DFIG. In this paper, a coil is offered to be integrated within the DFIG converters to improve dynamic performance of DFIG-based WECS during fire through fault within rotor side converter (RSC). Simulation results without and with the coil connected to the system are presented.

KEYWORDS: *Doubly Fed Induction Generator, Coil, fire-through & Wind Energy Conversion System.*

I. INTRODUCTION

Wind power has been one of the most important renewable energy sources over the former decade. According to global wind energy council (GWEC) statistics, more than 35 GW of new wind power capacity was brought online in 2013. The new global total at the end of 2013 was about 318GW representing cumulative market growth of more than 12.5 percent. Moreover, the global wind energy council forecasts that, at the end of 2016, global wind capacity will be around 493 GW [1]. In 2008, wind power has produced over 1% of the global electricity generation and by the year 2020; it is estimated to produce about 10% of the global electricity [2]. Currently, doubly fed induction generator (DFIG) is commonly used for wind turbines over 1 MW capacity [2]. DFIG based wind energy conversion system (WECS) is gaining popularity because of its superior advantages over other wind turbine generator concepts [3, 4] that have seen DFIG application in large WECS reaching 55% of the worldwide total wind capacity during the year 2012 [5]. A typical configuration of DFIG wind turbine is shown in Figure 1. Rotor side converter (RSC) and grid side converter (GSC) interface the DFIG with the grid [6]. Both converters use forced commutated power electronic switches such as insulated gate bipolar transistors (IGBT) to convert AC to DC and vice versa. A capacitor connected to the DC link of the converter acts as a DC voltage source [7, 8]. The failure of a wind turbine to remain operational for a short time of voltage dip without tripping is referred to the low voltage ride-through (LVRT) capability of the turbine. Rotor crowbar circuit is usually used to protect the RSC, which is relatively a cheap solution with simple control [5, 9, 10]. In addition, many papers in the literature have investigated various approaches to compensate WECS reactive power during voltage fluctuation events by mainly connecting a flexible AC transmission system (FACTS) device such as static synchronous compensator (STATCOM) to the point of common coupling (PCC) [11-17]. There are however a few publications considering compensation of active power as well [18-23].

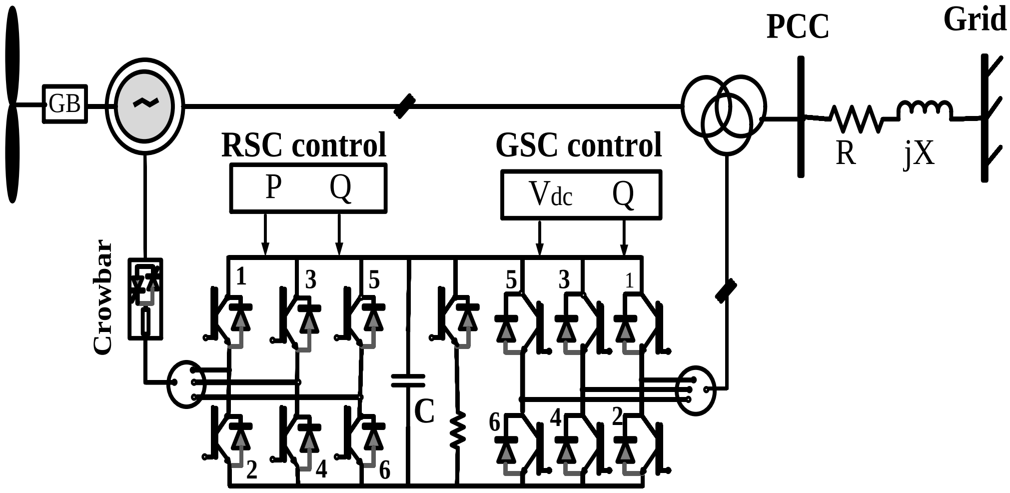


Figure 1. Typical configuration of DFIG

This paper presents a new topology for the DFIG converters by integrating a coil to improve the overall performance of a DFIG based WECS during internal converter switching malfunctions such as fire through fault within rotor side converter (RSC). Simulation is carried out using Simulink/Matlab software. The contribution of this paper lies in the use of the existing DFIG converters to support active and reactive power without the need to any extra FACTS devices as stated in the literature.

II. System Under System

Figure 2 shows the system under study that consists of six 1.5-MW DFIGs connected to the ac grid at the PCC. The grid that is represented by an ideal three phase voltage source of constant frequency is connected to the wind turbines via a 30-km transmission line and step-up transformer. During normal operating conditions, reactive power produced by the wind turbines is regulated at zero MVar to maintain unity power factor connection. For an average wind speed of 15 m/s, which is used in this study, the turbine output active power is 1.0 pu, and the rotor shaft speed is 1.2 pu [4]. A coil is connected to the DC link of the back-to-back power converters of the DFIG through a DC/DC chopper.

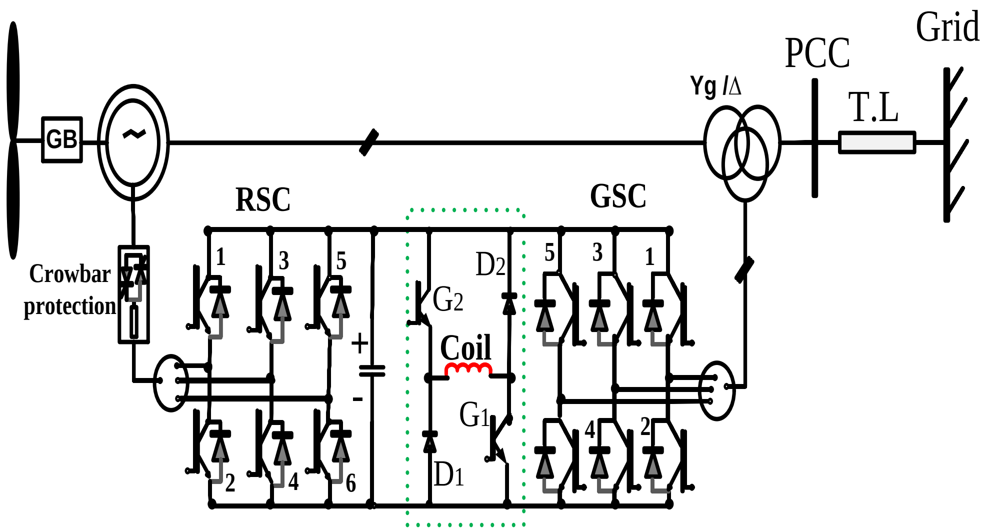


Figure 2. Configuration of a DFIG wind turbine equipped with a coil

III. COIL CONTROL ALGORITHM

To control the power transfer between the coil and the DFIG system, a dc–dc chopper is used, and a fuzzy logic model is developed to control its duty cycle (D) as shown in Fig. 3. Under normal operating condition, duty cycle is maintained at 0.5 and there is no power exchange between the coil and the grid. During internal RSC converter switching fault event that call for power support the FL controller acts to adapt the duty cycle to be in the range of 0 to 0.5 to allow the stored energy in the coil to be transferred to the grid (Discharging mode). The charging mode of the coil takes place when duty cycle is within the range of 0.5 to 1. The relation between the voltage across the coil Vc and the voltage across the dc-link capacitor V_{dc} can be written as [4, 24];

$$V_c = (1 - 2D)V_{dc} \tag{1}$$

The model is built using the graphical user interface tool provided by MATLAB. Each input is fuzzified into five sets of trimf-type membership functions (MFs). The MFs for the input variables, DFIG generated active power (P_g) and the current through the coil (I_c), are shown in Figures. 4(a) and (b), respectively. The MFs for the output variable, duty cycle (D), are considered on the scale from 0 to 1 as shown in Figure 4(c). Center of gravity is used for the defuzzification process where the desired output z_0 is calculated as

$$z_0 = \frac{\int z.u_{c(z)dz}}{\int u_c(z)dz} \tag{2}$$

where $\mu_c(z)$ is the MF of the output

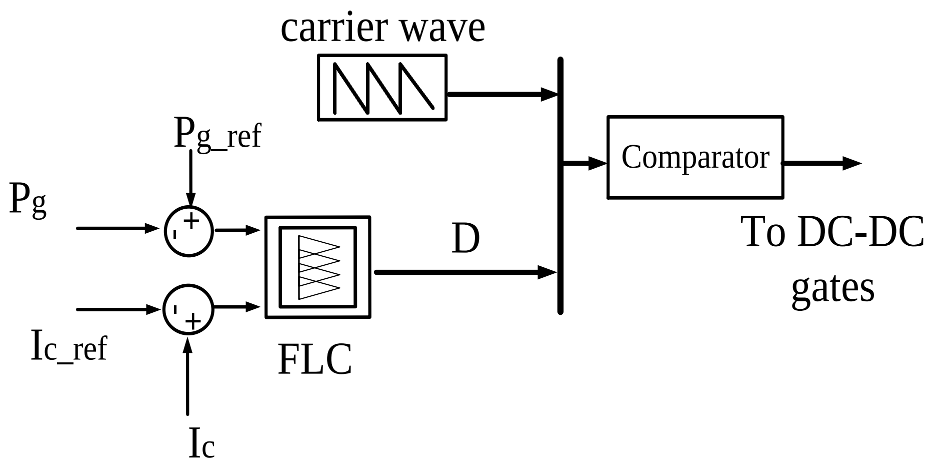
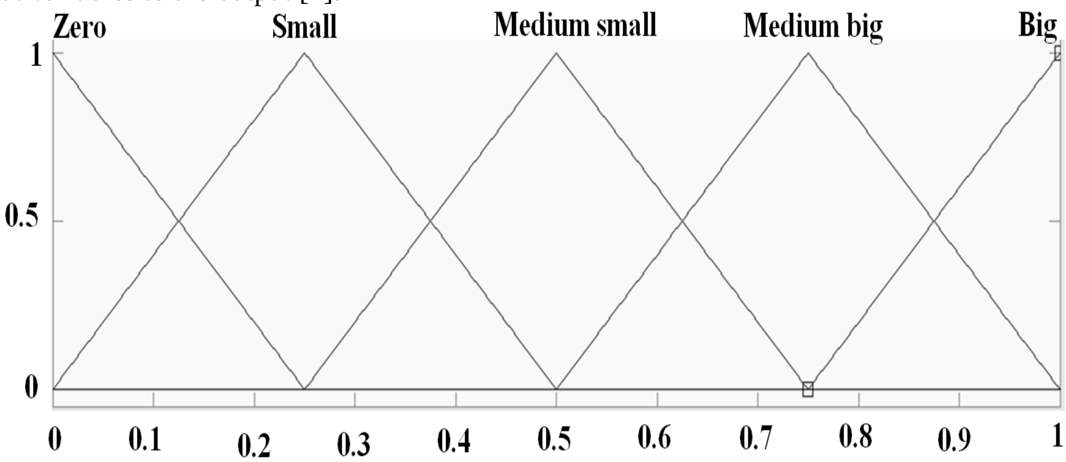
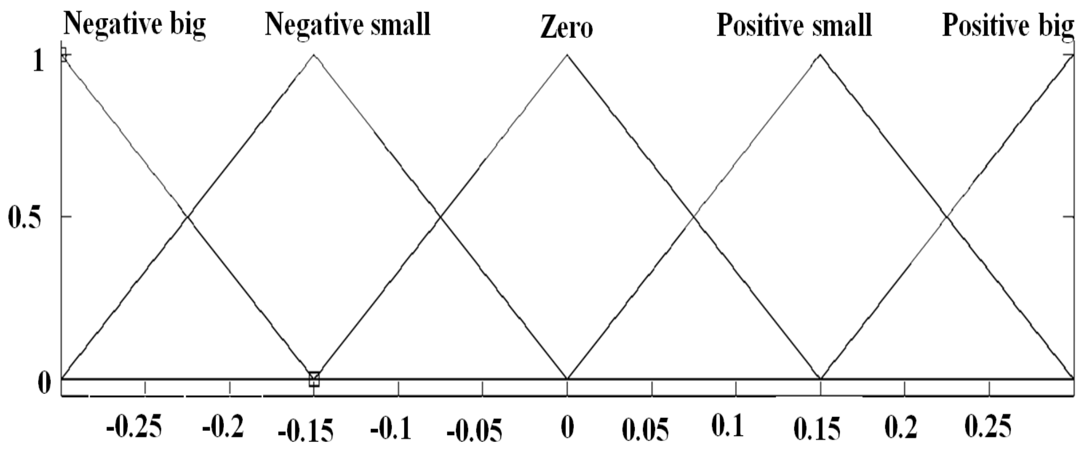


Figure 3. Control of DC–DC chopper

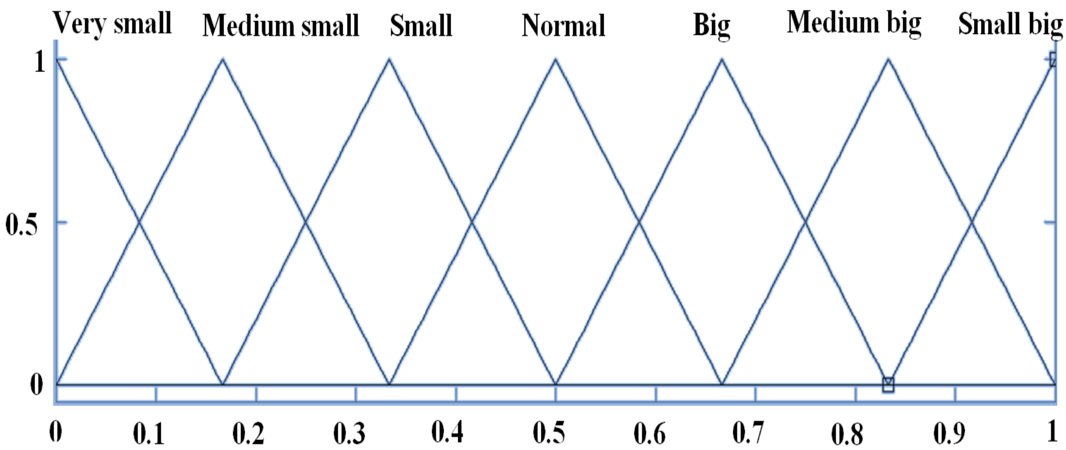
The variation range in the coil current and DFIG output power, along with the corresponding duty cycle, is used to develop a set of fuzzy logic rules in the form of (IF-ANDTHEN) statements to relate the input variables to the output [2].



(a)



(b)



(c)

Figure 4. Membership function for; (a) input variable Ic, (b) input variable Pg, and (c) output variable D

IV. COIL RESPONSES DURING THE FIRE THROUGH FAULT

There are three different modes of operation of the coil;

4.1. Freewheeling mode

Freewheeling (Standby) mode is shown in Figure 5(a), it occurs when D is equal to 0.5. The voltage across the coil (Vc) is equal to zero, and the Ic is held constant at its rated value; consequently, there will be no energy transferred between the coil and the grid, and maximum energy is stored within the coil. The voltage across the dc-link capacitor of the coil (Vdc) is maintained at a constant level during this mode of operation. This mode will take place during normal operating condition of the WECS and after the occurrence of the fault [4].

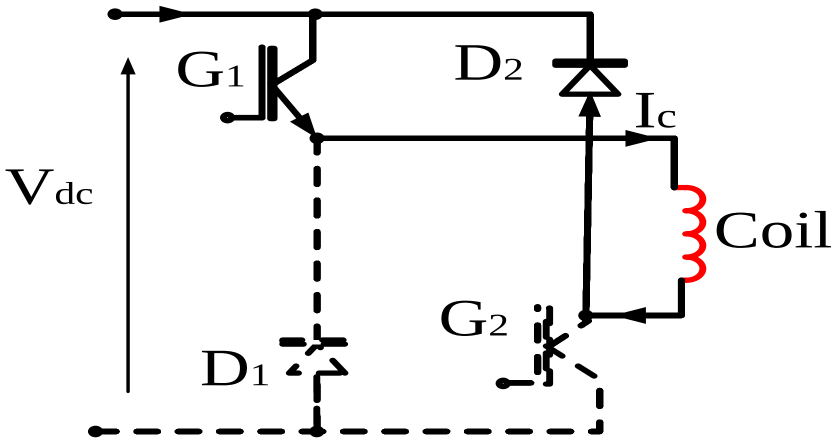


Figure 5(a). Freewheeling mode

4.2. Discharging mode

Figure 5(b) shows discharging mode which will take place when the fault occurs at the grid side. In this mode, the value of D lies in the range of 0–0.5. When the fault occurs at t =8 s, the current of coil (I_c) decreases, giving a negative slope (di/dt), and consequently, the voltage across the coil (V_c) is turning negative. The magnitude of the voltage across the coil is controlled by the level of the duty cycle, as well as the voltage across the dc-link capacitor as given in (1). The energy stored in the coil is being delivered to the grid during this mode, and the coil will be recharged at t = 8.06 s, exactly at the time when the fault is cleared according to the rules of the designated FLC for P_g and I_c [4].

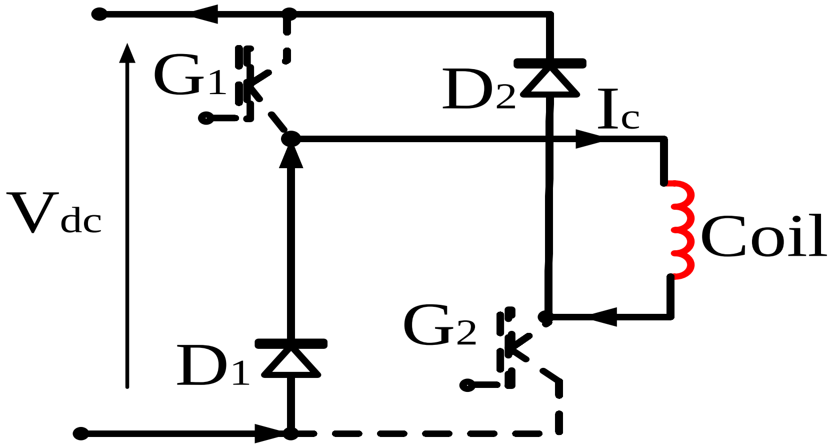


Figure 5(b). Charging mode,

4.3. Charging mode

In this mode, the coil is charged to its rated capacity. The value of D lies in the range of 0.5–1, and the coil current (I_c) increases, giving a positive slope (di/dt), and consequently, the voltage across the coil (V_c) is turning positive. The energy is transferred from the grid to the coil until the maximum coil energy capacity as shown in Figure5 (c) [2, 25].

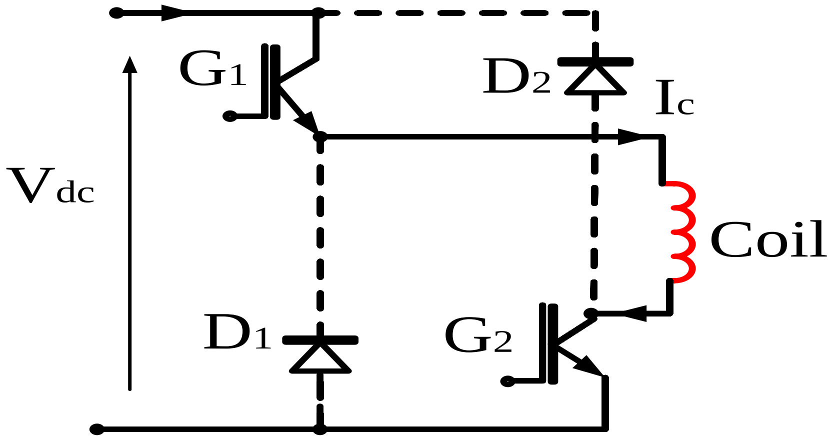
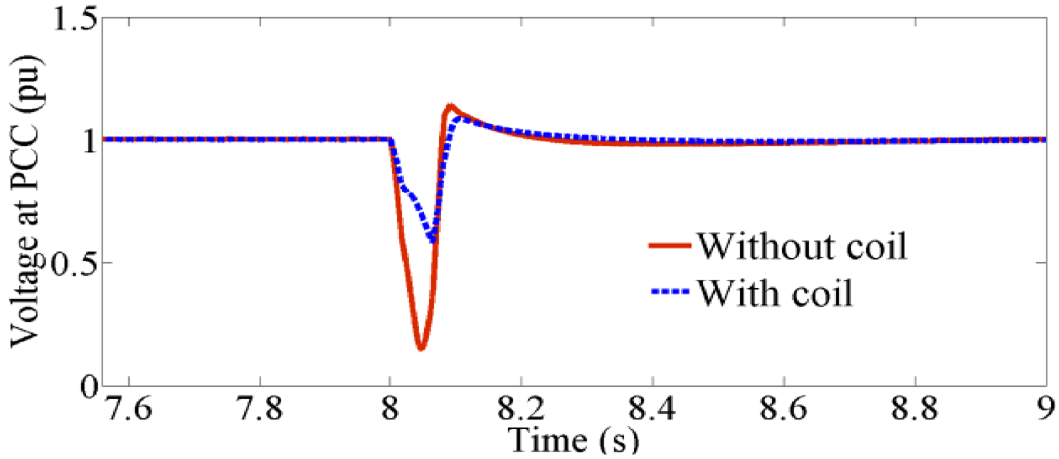


Figure 5(c). Discharging mode

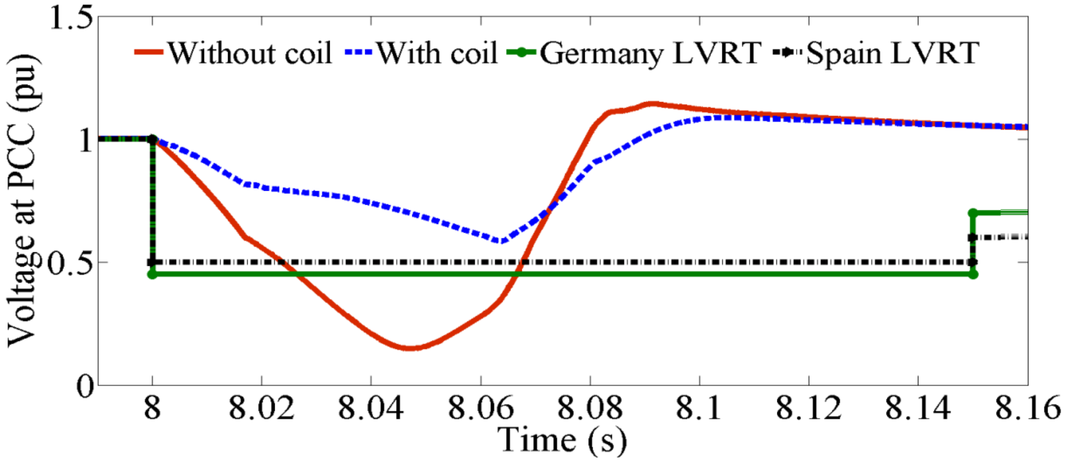
V. SIMULATION RESULTS

Intermittent fire-through is simulated within the RSC of the DFIG-based WECS shown in Figure 2. In studied case, the fault is assumed to occur on switch S1 at t = 8 s and cleared at t = 8.06 s. The model parameters are given in tables in the appendix.

Figures 6 through 11 show the dynamic response of the studied system when fire-through takes place within the RSC. The voltage profile at the point of common coupling (PCC) is shown in Figure 6(a), where without the coil, voltage will drop to 0.15 pu due to the fault. By integrating the coil within the DFIG converters, the dropped voltage at the PCC is raised to 0.59 pu due to the reactive power support by the coil. Compared with the fault ride through of Spain and Germany, the voltage at the PCC violates the LVRT of the two grid codes when the coil is not connected as shown in Figure 6(b). This will call for the disconnection of the wind turbine from the grid. However, with the coil, the amount of voltage drop decreases and reaches a safe level of the grids requirement Figure 6(b) and therefore the wind turbine connection to the grid is maintained.



(a)



(b)

Figure 6. Voltage profile at PCC

Due to the fire through fault and without the connection of the coil, the active power at the PCC will drop to -0.8 pu as shown in Figure 7. When the coil is integrated within the DFIG converters, it can be seen that absorbed active power at the PCC is decreased to be -0.2 pu during the fault as shown in Figure 7. Figure 8 shows the reactive power at the PCC without and with the integration of the coil from which the amount of surplus reactive power compensated by the coil is clearly observable.

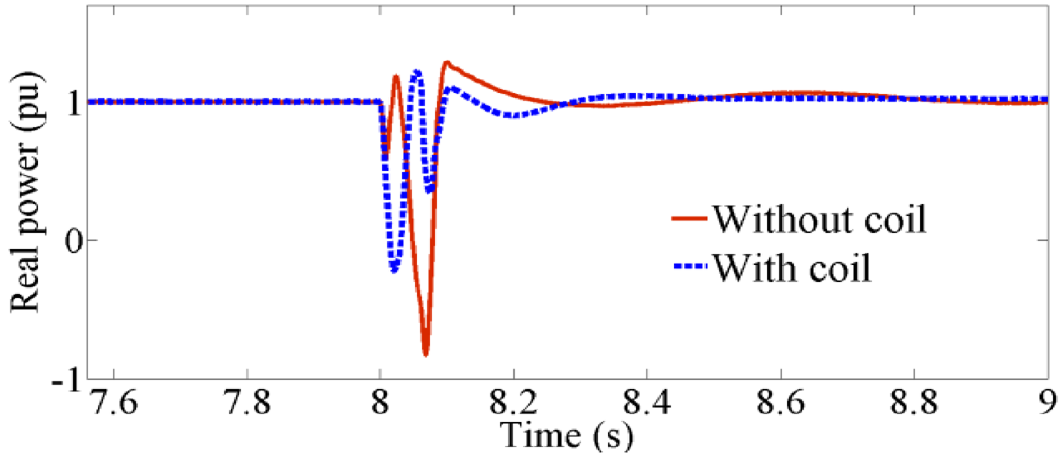


Figure 7. Active power

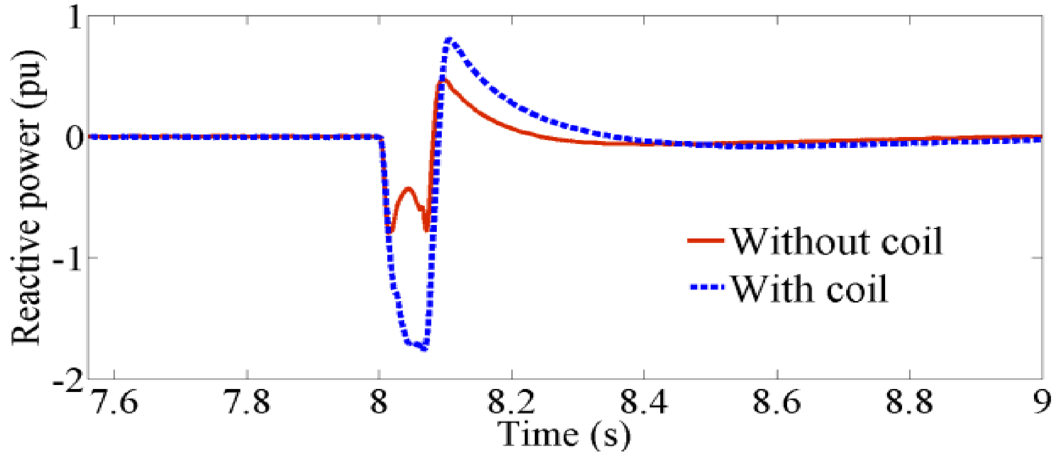


Figure 8. Reactive power

The voltage across the dc-link capacitor when fire-through fault takes place within RSC is shown in Figure 9 which reveals that the voltage across the capacitor drops to zero level during the fault and the voltage is recovered to its nominal level upon fault clearance.

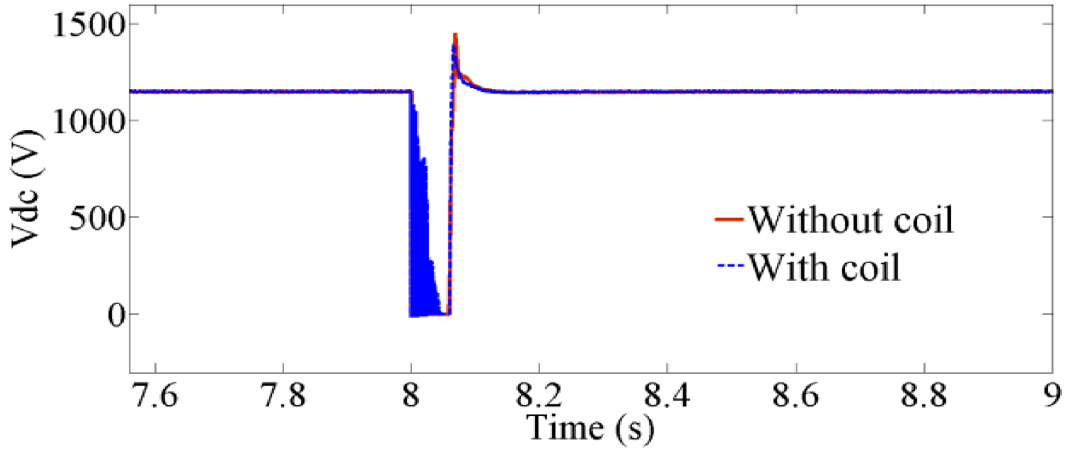
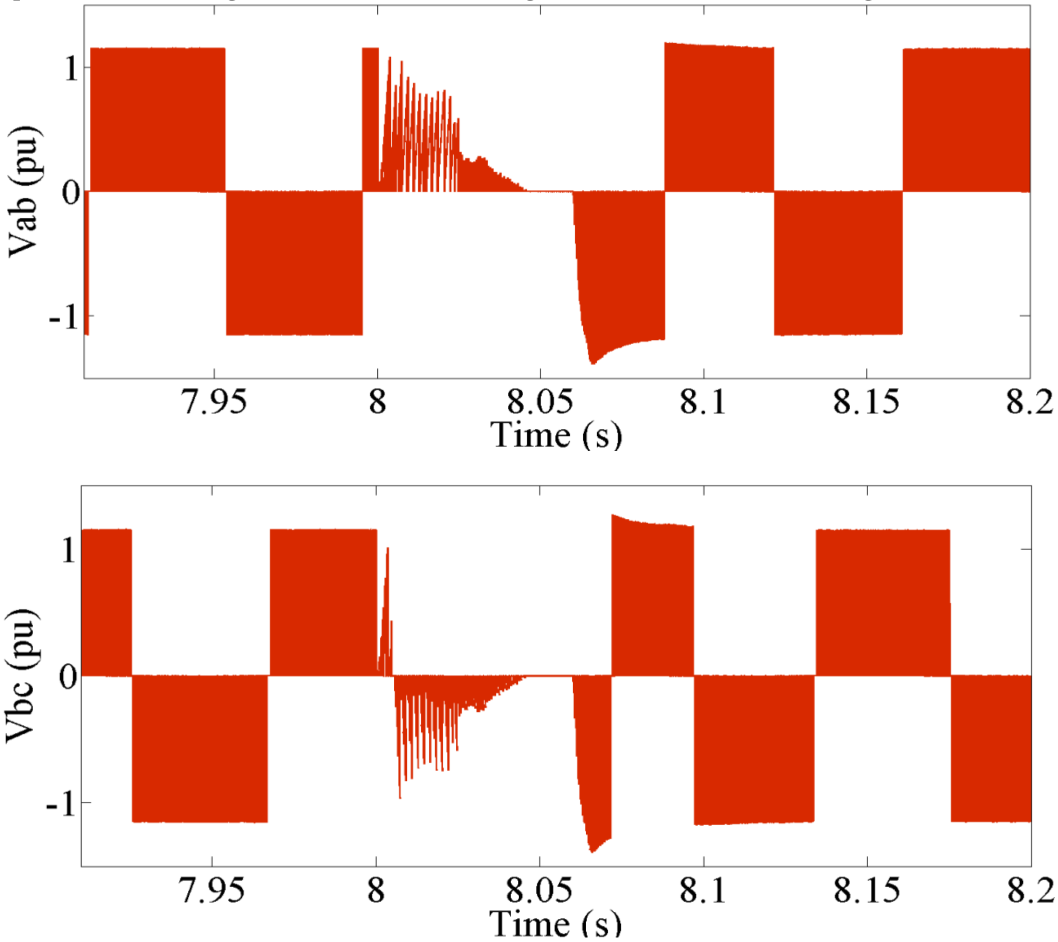


Figure 9. DFIG dc-link voltage

The impacts of fire-through fault on terminal voltages of RSC can be seen in Figure 10.



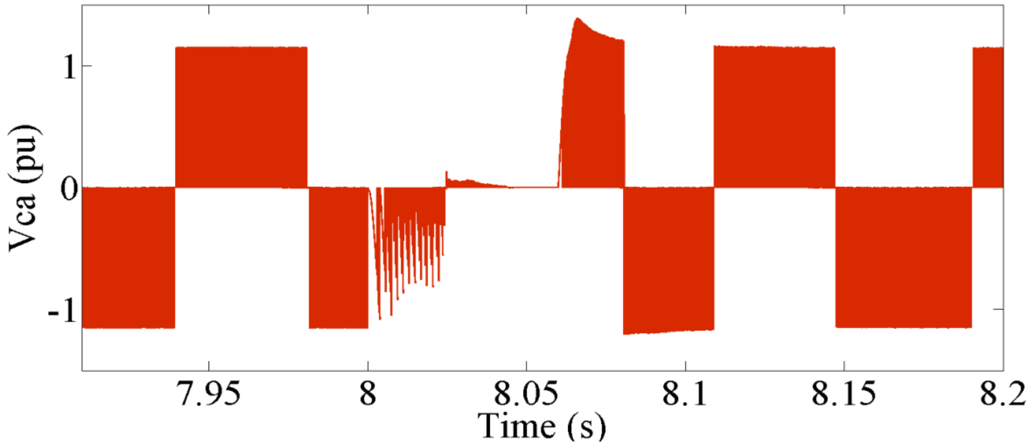


Figure 10. Voltage across RSC terminals during fire-through in S1within RSC.

The coil behavior when fire-through occurs within GSC can be investigated through Figures 11 to 13 which respectively show the voltage across the coil (V_c), coil current (I_c), and coil stored energy ($E_{coil} = 0.5L_cI_c^2$) [26]. Before the fault application and during normal operating conditions, the duty cycle is maintained at 0.5 and the voltage across the coil is maintained at zero level which is corresponding to maximum coil current and rated stored energy. Upon the occurrence of fault, the proposed controller acts to reduce the duty cycle to a level less than 0.5 that creates a negative voltage across the coil and the current will be reduced accordingly allowing portion of its stored energy to be delivered to the grid. When the fault is cleared the fuzzy logic controller acts to retain the duty cycle level to 0.5 again.

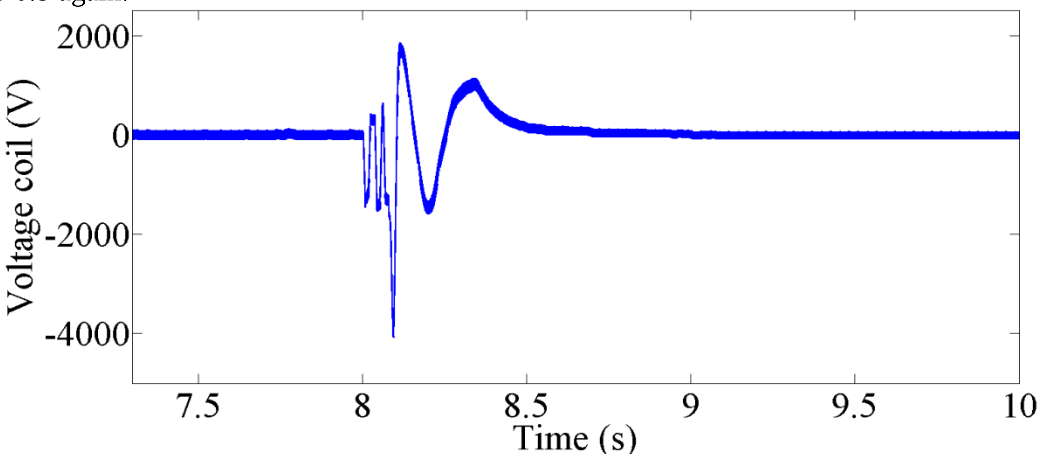


Figure 11. Voltage across coil

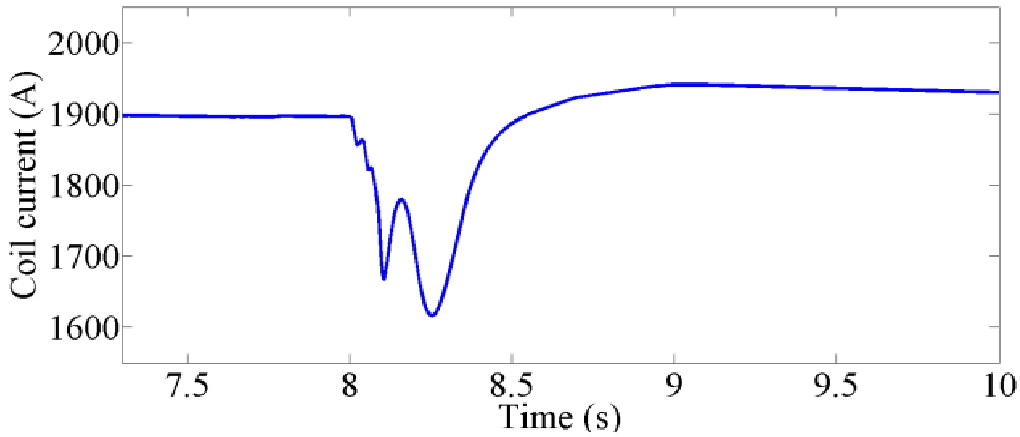


Figure 12. Coil current

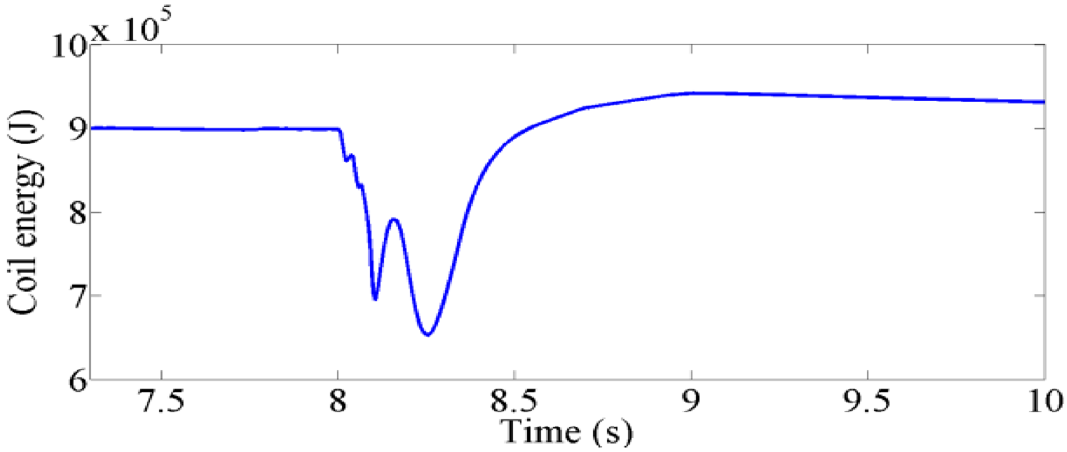


Figure 13. Stored energy of coil

VI. CONCLUSION

This paper presents a new topology for the DFIG converters by integrating coil within the dc-link. A fuzzy logic controller is employed to control the exchange of energy stored in the coil with the grid through controlling the duty cycle of the DC-DC chopper interfacing the coil with the converters dc-link. Results show that the proposed topology can improve the dynamic performance of the DFIG-based WECS during fire through fault within RSC without the need to connect an additional FACTS device as proposed in the literature. The proposed controller is effective and easy to implement.

APPENDIX

Table I. PARAMETERS OF DFIG

Rated Power	9 MW (6 x 1.5) MW)
Stator Voltage	575 V
Frequency	60 Hz
R_s	0.023 pu
R_r	0.016 pu
V_{dc}	1150 V
V_{pcc} Base Value	25 kv

Table II. PARAMETERS OF TRANSTION LINE

R_1, R_0 (Ω/km)	0.1153, 0.413
L_1, L_0 (H/km)	1.05 x 10-3, 3.32 x 10-3
C_1, C_0 (F/km)	11.33 x 10-9, 5.01 x 10-9
Line length (km)	30

Table III. Parameters Of Coil

L_c	0.5 H
Rated I_c	2000

VII. FUTURE WORK

Based on the results published in this paper, more applications of the new topology proposed in this paper can be investigated. Also, the controller can be improved.

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