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Research paper

Opal-RT based Analysis and Implementation of DFIG with Standalone Wind Energy Conversion System

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Abstract

In this paper, the detailed analysis and performance of a vector oriented control topology in Doubly-Fed Induction Generator (DFIG)-based wind power generation systems is discussed in order to produce a high quality of output voltage. The distortion of voltage and frequency control capabilities in both stator side and rotor-side converters (SSC&RSC) for unbalanced network condition are investigated. The control scheme is implemented in the synchronous rotating reference frame and provides specific current control for both the SSC and RSC. The primary objective of the control scheme is to maintain constant voltage and frequency under variable wind speed and operating conditions of load. Thus this technique is found to be capable of achieving minimum harmonic voltage distortion, thereby resulting in a nearly sinusoidal waveform to improve the power quality of the systems. The performance of the suggested topology is validated in real time environment using Opal-RT Lab simulator and adequate results were taken.

Keywords: *DFIG, Wind Speed, Vector Oriented Control, SWECS, Opal RT,*

1. Introduction

The novel changes in atmosphere around the world have made it required for worldwide group to diminish their carbon impressions. Renewable energy
resources [1,], both for grid-connected and isolated locations [2], have pulled in overall consideration because of expansive costs and quick decrease of petroleum derivatives and environmental change concerns. Sustainable power source assets are contemplated suggestive in expounding the security of vitality supplies by reducing the reliance on petroleum products and falling the outflows of greenhouse gases (GHG).
There are a large number of human habitats in the world, where grid-fed electrification is often unviable or uneconomical [3-4] requiring autonomous systems. A suggestive section of one billion Indian populations does not have grid fed electricity. Although massive rural electrification has been carried out since independence (1947), all villages are not electrified. Even in the electrified villages, reliable supply is not guaranteed throughout the day with varying periods of blackouts due to deficient generating capacity and transmission line problems. There are many un-electrified consumers in many of these electrified villages. For such remote and rural communities, off grid or autonomous power generation using locally available renewable energy sources can be a viable option provided capable technologies are developed that are reliable, environment friendly and economical. It is observed in such cases, stand-alone wind energy conversion systems (SWECSs) may be a sustainable option for the power generation.
The variable speed WECS's with a DFIG coupled through gearbox are more popular due to their ability to produce larger amount of energy than constant speed WECS [5]. In Fig.1.1 demonstrates the DFIG based wind turbine with consecutive associated voltage source converters (VSCs) between the stator and rotor circuits have been studied as a standard option with reduced rating converters for variable speed generating systems involving limited speed range [6]. The DFIG is capable to handle power more than the rated power of the machine beyond the rated speed in super-synchronous generation due to slip energy recovery.

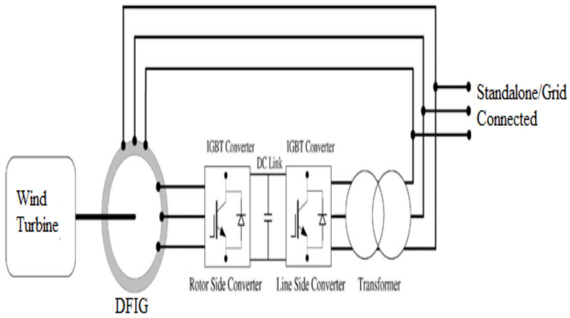

Fig. 1 DFIG connected Wind Turbine

In the grid connected variable speed WECS incorporating MPT and using DFIG the bidirectional dynamic power stream ability is finish up by the utilization of two voltage source converters (VSCs) are interfaces with a typical capacitive dc link. On the other hand, in autonomous systems, the issues of VFC are required to be addressed in the wake of varying loads and wind speeds.

2. Control Algorithm in both side converters

2.1 Control of Rotor- Side Converter

In a DFIG machine with a current controlled PWM voltage source converter has been accounted for broadly [7]. The rotor current can be managed in frequency, adequacy with a controlled converter at rotor terminals by reasonable use of rotor voltage from the rotor side converter.

For decoupling the active and reactive current control loops, the stator flux situated frame of reference is utilized. In Fig. 2, it can be seen the d-axis is situated along the grid flux axis while the q-axis (lagging the d-axis by 90◦) is arranged along the stator voltage vector. The q-axis current loop manages the torque of the machine by controlling the dynamic power flow. Then again, the d - axis directs the reactive power flow in this way controlling the flux in the machine[12].

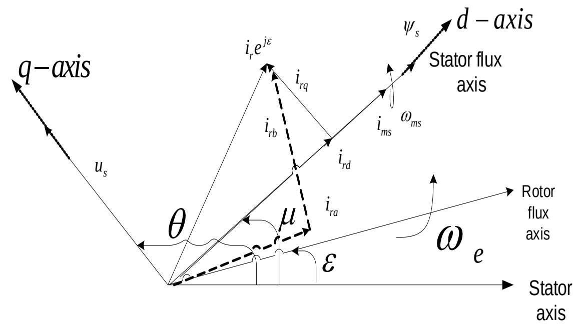

Fig. 2 Vector diagram of field oriented control

The dynamic equations governing the rotor currents in the stator flux coordinates [8], are as follows:

$$\sigma T_r \frac{di_{rd}}{dt} + i_{rd} - \frac{u_{rd}}{R_r} = (\omega_{ms} - \omega_e)\sigma T_r i_{rq} - (1-\sigma) T_r \frac{di_{ms}}{dt} \quad (1)$$

$$\sigma T_r \frac{di_{rq}}{dt} + i_{rq} - \frac{u_{rq}}{R_r} = -(\omega_{ms} - \omega_e)\sigma T_r i_{rd} - (\omega_{ms} - \omega_e)(1-\sigma) T_r i_{ms} \quad (2)$$

Where

$$\sigma = 1 - \left(L_m^2 / L_s L_r \right)$$

and σ (= 1 − (1/ (1 + σ_s) (1 + σ_r) is the leakage factor and T_r (= L_r/R_r) is the time constant of rotor circuit of machine. these can be consider for grid flux also if the stator resistance drop is negligible.

These equations (1) and (2) are used to generating the d and q axis current control loops in the rotor side converter. To controlling the rotor side d and q axis current, the cross-coupling terms between the d-axis and q-axis $(\omega_{ms} - \omega_e)\sigma L_r i_{rq}$ and $(\omega_{ms} - \omega_e)\sigma L_r i_{rd}$ and unsettling influence input $(\omega_{ms} - \omega_e)(1 - \sigma)L_r i_{ms}$ are drop by encourage forward recompense and in this manner autonomous control of d-axis and q-axis current circles is finish up by including PI controllers on the loop[9].

2.1.1 q-Axis Rotor Current

The active part of the stator current i_{sq} is estimated; the reference for the q axis segment of the rotor current is

$$i_{rq} = (1+\sigma_s) i_{sq} \quad (3)$$

2.1.2 Voltage Loop

The magnetizing current vector (i_{ms}) in charge of creating the stator flux is directed to control the stator
voltage size. The conditions of magnetizing Current under elements and enduring state condition are

$$T_s \frac{di_{ms}}{dt} + i_{ms} = (1+\sigma_s)\frac{u_{sd}}{R_s} + i_{rd} \quad (4)$$

$$i_{ms} = (1+\sigma_s) i_{sd} + i_{rd} \quad (5)$$

The equation (5) is aggregate magnetizing current i_{ms} of the machine is provided from the rotor side converter by d-axis rotor current i_{rd} is required for no underlying grid. An outer voltage circle is required to controlling the extent of i_{ms} for controlling the stator voltage through d-axis current control circle. The magnetizing current i_{ms} controls the extent of u_{sq} part of stator voltage which is driving it by 90◦ as show in figure.3 [10].

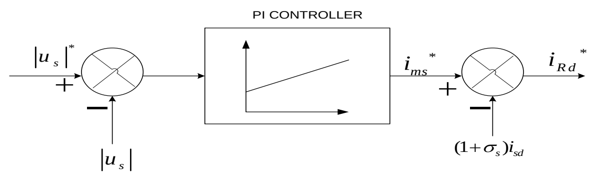

Fig. 3 configuration of voltage control loop

2.1.3 Design of Frequency Loop

To manage the grid frequency, the frequency loop is required. At first, unit vector generation scheme utilized for created unit vectors presented in equation (6). With the assistance of unit vectors, the grid network frequency is evaluated utilizing the accompanying condition:

$$\omega_{ms} = \cos(\theta)\frac{d}{dt}\sin(\theta) - \sin(\theta)\frac{d}{dt}\cos(\theta) \quad (6)$$

The output of the slip frequency order is basic to be associated from the rotor side converter to keep up enduring stator frequency. Variation in prime mover speed will reflect in variation in organize frequency for a consistent rotor frequency. The ability in frequency is distinguished and restore move is made by the controller to pass on back the stator frequency to the apparent set value.

2.2. Control of Stator Side Converter

The objectives of the stator side converter to keep up the dc interface voltage. It is a current controlled voltage source converter. The rotor reference layout based field-arranged control in affixed to the stator voltage vector are controlled the line currents. The q-axis is agreed with the stator voltage vector,, while d-axis is slacking by 90◦ to keep up comparability with the rotor side converter control in Fig.4.

2.2.1 Design of Voltage and Current Loop

The q- axis and d-axis line currents equations [8] are

$$T_{fe}\frac{di_{feq}}{dt} + i_{feq} = -\frac{u_{feq}}{R_{fe}} + \frac{u_{acq}}{R_{fe}} - \omega_s T_{fe} i_{fed} \quad (7)$$

$$T_{fe}\frac{di_{fed}}{dt} + i_{fed} = -\frac{u_{fed}}{R_{fe}} + \omega_s T_{fe} i_{feq} \quad (8)$$

Where T_{fe} $(= \frac{L_{fe}}{R_{fe}})$ is the time constant of filter. The above equations are used in line side converter to provide inner current control loops. The d- and q-axis

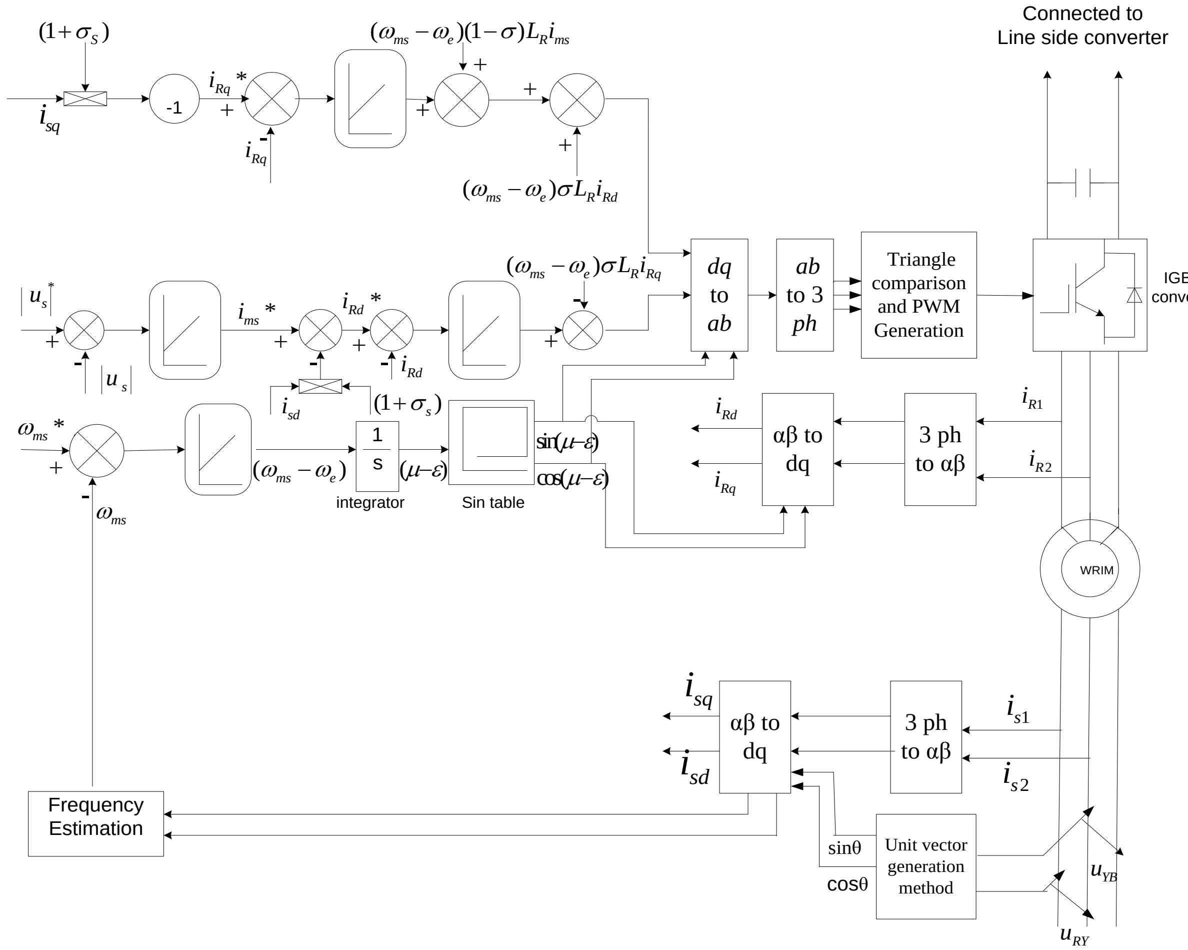

Fig. 4 Block Diagram of Rotor side Converter

current loops responds are prepared self-determining by cancel out through feed forward compensation of

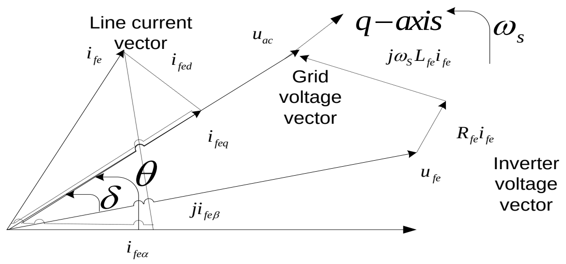

Fig. 5 Vector Diagram of Stator side Converter

cross-coupling terms ($\omega_s L f_e i_{fed}$ and $\omega_S L_{fe} i_{feq}$) and disturbance input (u_{acq}) in the loops. The tuning of PI controller to control current in the loops.

2.2.2 Slip Frequency Operation

This is a piece of frequency loop to produced unit vectors. In this scheme created slip frequency order ($\omega_{mS} - \omega_e$) exhibited at the output of the frequency controller is joined to get slip angle information ($\mu - \epsilon$). The unit vectors sin ($\mu - \epsilon$) and cos ($\mu - \epsilon$) to actualized the entire field situated control and no different speed or position sensors are required for the control conspire. The scheme is appeared in Fig. 6

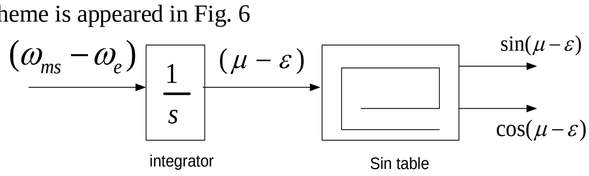

Fig. 7 Slip frequency unit vector generation

2.2.3 Calculation of Slip Angle

$$\theta_{slip} = \theta_e - \theta_r = \int \omega_e^* dt - \theta_e \tag{9}$$

Where θ_r is measured using a encoder. eqn. (7) forces the stator flux to rotate at the demand frequency during both steady state and dynamic conditions for any shaft speed.

Table 1: Rating of Three-Phase Doubly Fed Induction Machines

S.No.	Power Rating(kW)	Connection	Line Voltage(V)	Line Current(A)	Freq./Pole
01	3.7	Y	230	16	50/4

Table 2: Equivalent-Circuit Parameters (Per-Phase) of Machine

Power Rating(kW)	R_s (Ω)	R_r (Ω)	L_{ls} (H)	L_{lr} (H)	L_m (H)
3.7	0.3939	0.491	0.0020164	0.002514	0.07665

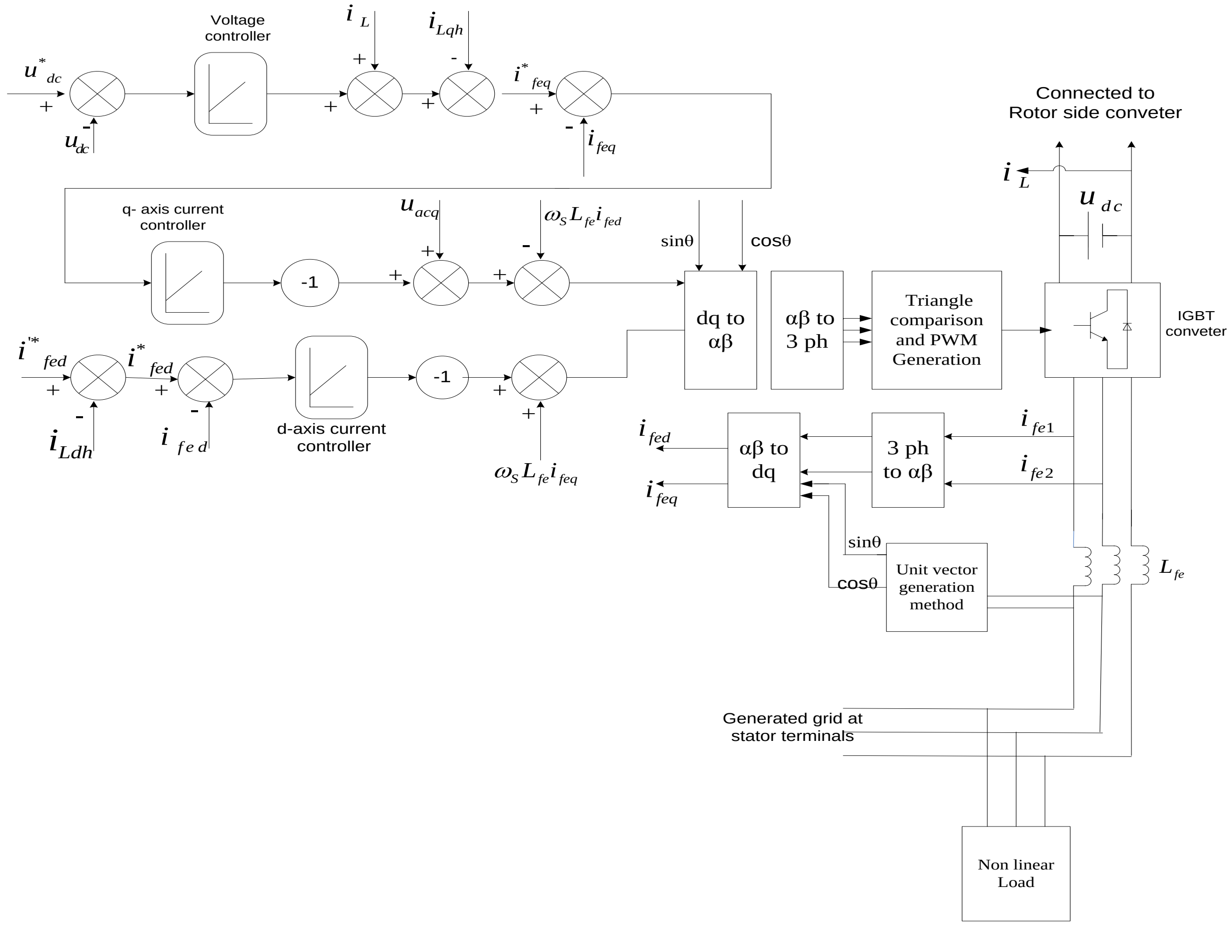

Fig. 8 Block diagram of line side converter

Table 3: Rating of Controller Parameters

DC link voltage (battery)(V)	Transformer(KVA),(V)	Inductor (H)
100	2,230/100	2e-3

3. Matlab Simulink Model of DFIG Based SWECS

The Simulation Model of Vector control of DFIG for SWECS in variable wind speed operation were conducted on a 3-ϕ, 4-pole, 50Hz, 230V, 3.7KW machine is shown in Fig.8.

3.1 Subsystem of Rotor side converter

Fig. 8 has shown the simulink diagram of subsystem of rotor side converter with the help of MATLAB Simulink Power stem toolbox. The input to vector control block are i_{rd} and i_{rq} which is generate through rotor side three phase current i_{rabc} conversion of abc to dq reference frame. Another input fed to rotor side converter is d-q axis current of stator side converter by abc to dq conversion with the help of slip angle θ which is difference between stator and rotor speed. The rotor side converter is used to generate d axis rotor current i_d and magnetizing current i_{ms} and second block generate the q axis rotor current i_q . the i_d and i_q current of rotor side to conversion in three phase current i_a,i_b,i_c for applying switching pulses of rotor side converter.

The first subsystem generation of magnetization current i_{ms} is controlled by tuning of PI controller to comparison of three phase voltages w.r.to constant voltage. The d axis current i_d is controller another PI controller to compare rotor side d axis component of current, which is shown in Fig. 8. The generation of q axis rotor current i_q are controlled by tuning of PI controller which is given by comparison of reference and feedback signal of q axis rotor current component as shown in Fig. 8. to provide three phase current i_a,i_b,i_c through dq to abc conversion. The three phase current to generate the switching pulse of three phase rotor side converter through proper tuning of PI controller as shown in Fig. 8.

3.2 Sub system of Stator Side Converter

Fig. 8 shows simulink model diagram of the stator side converter which is mostly used to produce DC link voltage to the converters of the DFIG. This is done by maintaining the voltage and frequency is constant under variable load condition. It is required to three phase current to convert dq transformation and again convert to dq to abc transformation to generate switching pulse in stator side converter.

The generation of q axis stator current i_{sq} are controlled by tuning of PI controller which is given by comparison of reference and feedback signal of q axis stator current component. to provide three phase current i_a,i_b,i_c through dq to abc conversion. The three phase current to generate the switching pulse of three phase stator side converter through proper tuning of PI controller.

4. Validation with OPAL RT Environment

The OPAL-RT test systems, outfitted with the OP5600 chassis, is an entire reproduction framework containing a capable continuous target PC furnished with up to 12 parallel 3.3 GHz processor center, an adaptable extensive speed front-end processor and a flag molding stage. Fig. 10 demonstrates the real time simulation test bench utilized as a part of this work. A stage to test operation of DFIG drive, which include the model of DFIG Generator with the different estimation techniques and adaptive mechanism, with power electronics device in RTDS controller and generate the signal in PC and a communication interface between them[11].

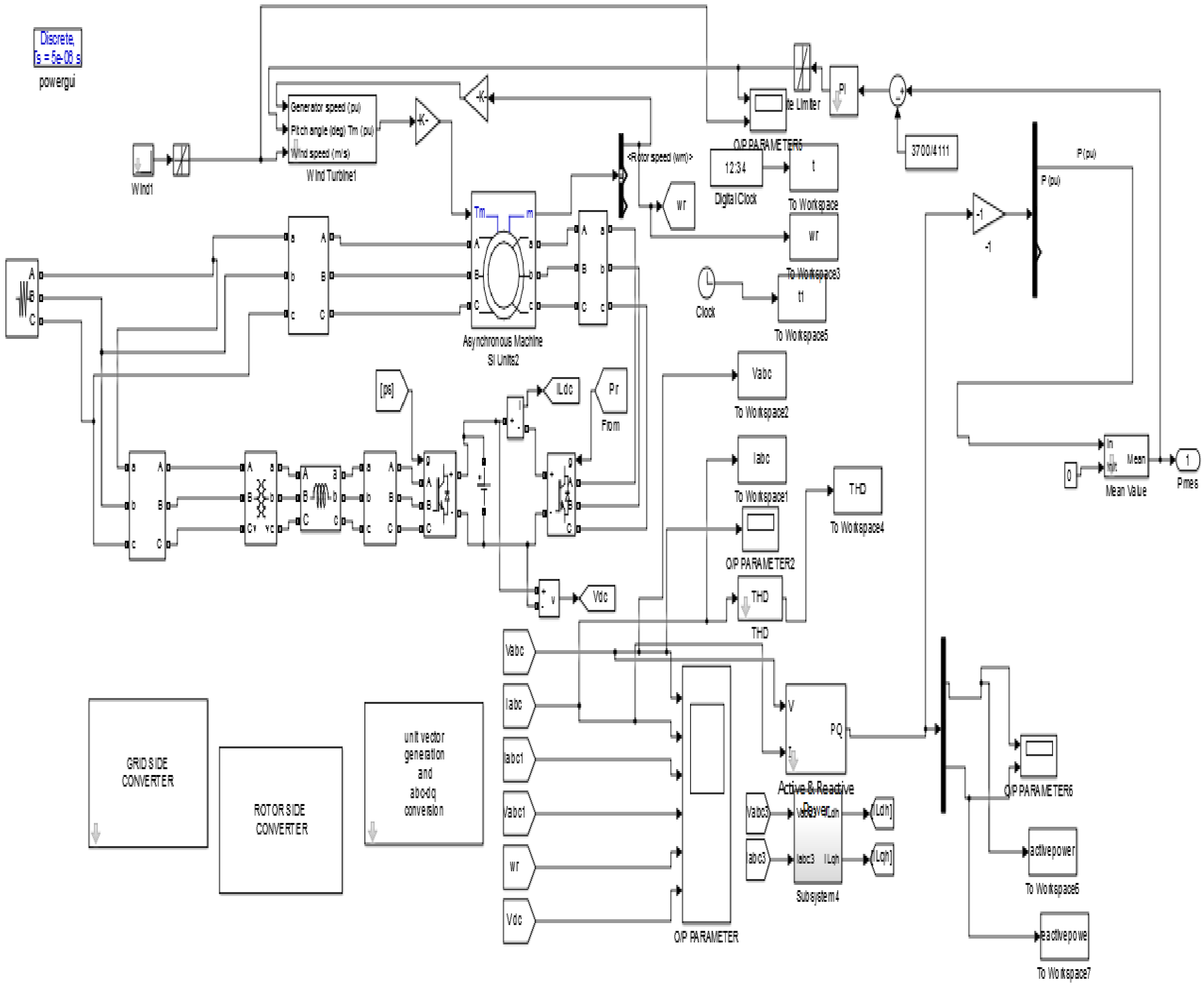

FIG. 9 Simulation model of DFIG with back to back PWM converter

4.1 Depiction Of DFIG Model for Real Time Simulation

The Opal-RT enables designers to demonstrate their thoughts, models and last items in a sensible domain. Right off the bat, the DFIG display with vector control scheme with various versatile system as talked about in the past part is demonstrated in MATLAB, as the OPAL-RT eMEGAsim is coordinated with the MATLAB/Simulink. It is ordered with the RT-LAB to keep running as a compelling stage for creating and testing constant DFIG Generator. In spite of the fact that the model inherent MATLAB/Simulink condition can easily run, still it basic some basic adjustments to make the model skilled for the ongoing activity mode in RT-LAB condition. The RT-LAB test system [10] engages the parallel simulation vitality drives and electric circuits on bundles of PC running lively UNIX (QNX) or RT-Linux looking after structures. Using standard Simulink models, RT– LAB makes count and correspondence errands essential to make parallel simulation of electrical structures with standard PCs and correspondence joins. To execute the model on a couple of focuses, it should be confined in different subsystem assumed as master, slave and console system, for social event by RT-Lab.

Each expert and slave subsystem in RT-lab is designated to an alternate focus to play out their parallel methodology in gainful

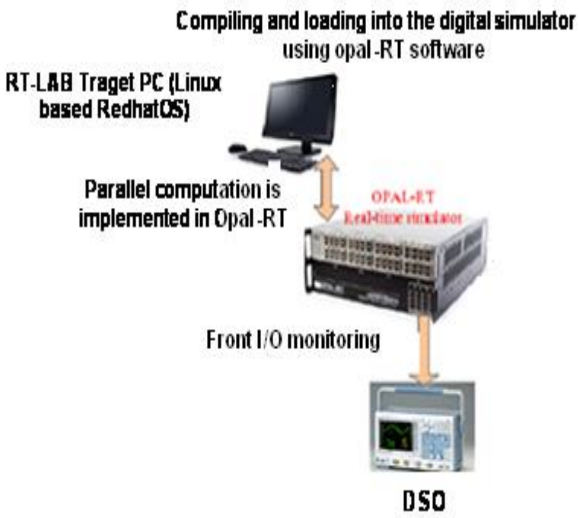

Fig. 10. Opal-RT and RT-Lab Architecture

and speedy way. By the day's end, each subsystem is coded in C lingo and worked for execution among its processor. After game plan, the code is stacked into the target hardware and executed by methods for parallel dealing with.

As appeared in Fig. 11, the model is isolated into two subsystems. The registering (ace) subsystem named SM_MODEL NAME contain all the count squares, which keeps running on the objective processor with the constant supporting framework as appeared in Fig. where as the console subsystem named SC_MODEL NAME contains every one of the pieces used to show and direct particular signs, which keep running on the host PC. In view of this the regular DFIG demonstrate with versatile PI controller with display name as "DFIG" for free Wind vitality Conversion system is showed up in Fig. 12.The comfort

Table 4 Scaling Parameters

Trace Parameters	Actual Value	Scaling Value
Reference/Actual speed	1500rpm	10 rpm
Reference/Actual Output Voltage Reference/Actual Output Current	325V 14A	10 V 10A
Reference/Actual Active Power Reference/Actual Reactive Power Reference/Actual DC Link voltage	2000W 1500W 100V	10W 10W 10V
Actual/Estimated Generator speed	157rad/sec	10rad/sec

subsystem is supporting on the summon station and interfacing with the DFIG structure on the OPAL-RT. Most of the discernments in indicate squares are sent through I/O channels for watching and recorded by a Digital Storage Oscilloscope (DSO).To make the model practicable in RT-LAB stage, some fundamental modules should be added to the subsystems. A discrete settled advance size of 50 µs is utilized to register the proposed controller. In every one of the tests, the measured factors accessible in controller block running on real-time digital simulator were downsized as given in Table 4, Estimated factors from checking ports of the ongoing real-time digital simulator at that point specifically showed on the DSO. Thus in light of decide actual value of a variable, the DSO reading must be increased by scalingparameter.

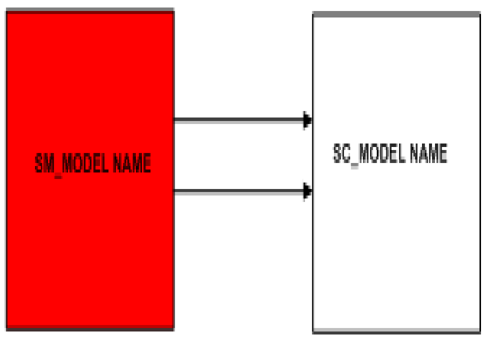

Fig. 11 Typical modelling of MATLAB/Simulink block in RT-Lab

Apart from the conventional blocks available in Simulink library the other necessary blocks available in RT Lab I/O library like OpComm and Opmonitor as shown in Fig. 12 are included in the real-time work.

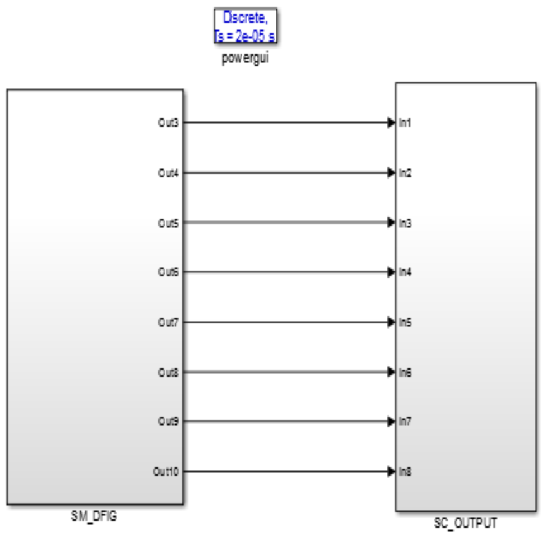

Fig. 12 Implementation of DFIG with SWECS in RT-Lab

4.2.1 Validation of Proposed Methodology

For real-time simulation, the DFIG based SWECS model with the Vector Control scheme using in stator and rotor side control for isolated load application is developed, one is acting as master unit and other is acting as slave unit. The developed model is simulated in OPAL-RT with the fixed step size of 20 µs as the ARTEMiS software provides fixed-step solver dedicated to complex electric system.

Fig. 13 shows the results of an DFIG Generator depicting the load changes condition. when the linear load is 1000w,the generator speed is slightly increase to 156.5 rad/sec to maintain the constant speed at that time wind speed is 9m/sec.the 3-phase output voltage and frequency at load side are measured in constant, although producing more harmonics distortion. In this condition the measuring 3-phase output voltage V_{abc} at 320v and 3-phase output I_{abc} is 13A.

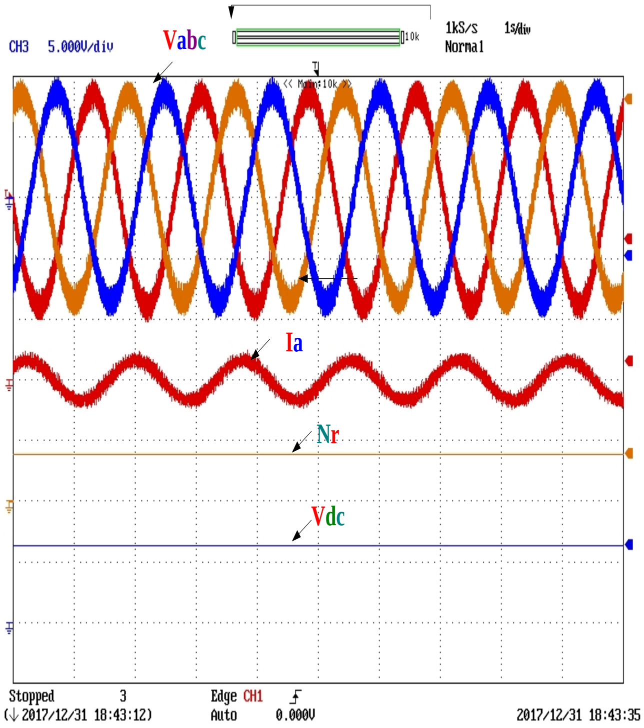

Fig. 13 CH1&2:5V/div (*Vabc*), CH3&4:5V/div (Ia), CH5&6: 20V/div

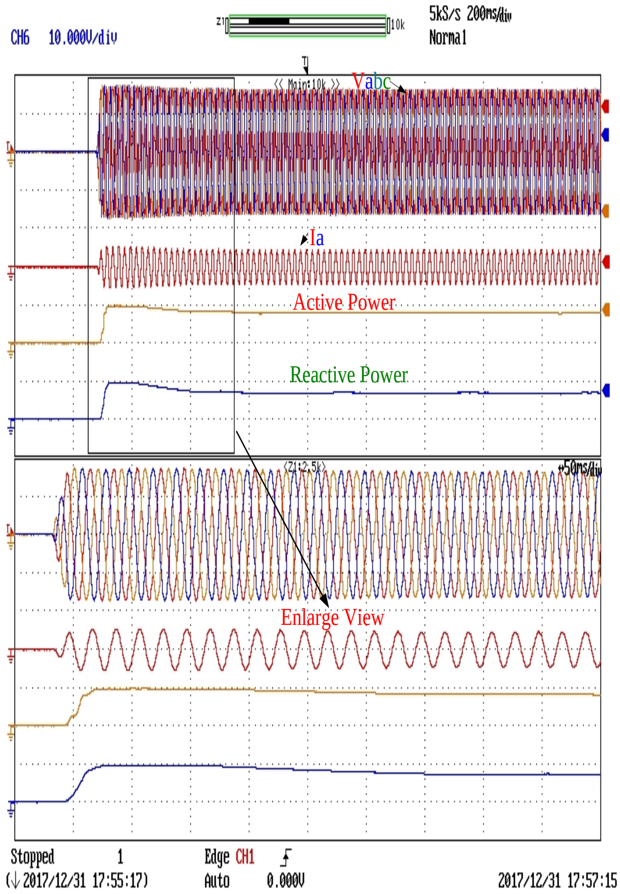

Fig. 14 CH1&2:10V/div (**Vabc**), CH3&4:2V/div (Ia), CH5&6: 10V/div(P&Q)

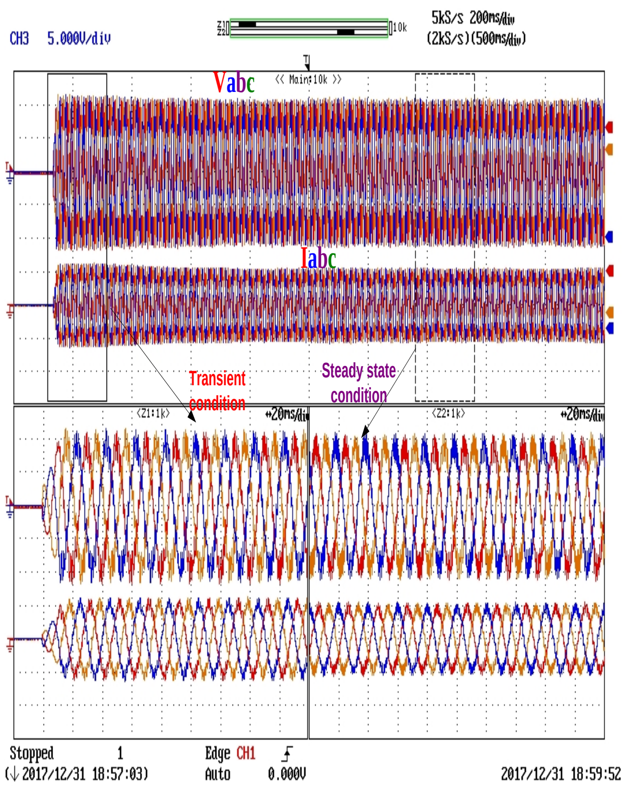

Fig. 15 CH1&2, 3:5V/div (V_{abc}), CH4&5, 6:10V/div

(I_{abc})

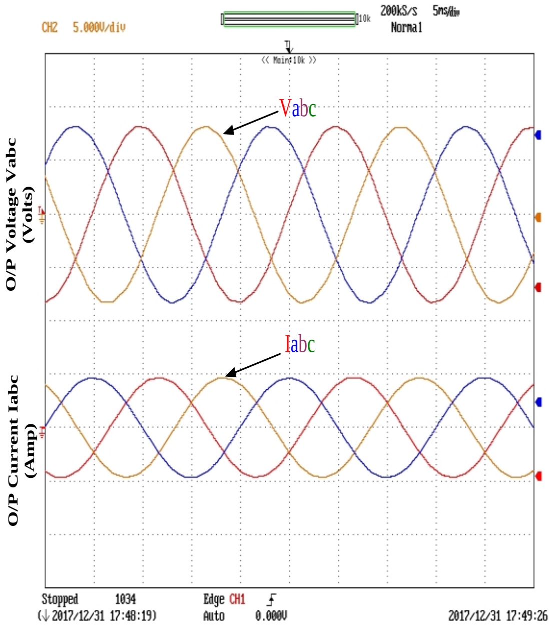

Fig. 16 CH1&2, 3:5V/div(V_{abc}), CH4&5,6:10V/div (I_{abc})

Fig. 16 shows the results of DFIG based SWECS under variable load condition is consider the linear load is 3000 W, the generator speed slight decrease to 155 rad/sec. the unit vector generation scheme are used slip frequency estimation technique to established the 3-phase output voltage V_{abc} and 3-phase output current Iabc are controlled by magnetizing current component I_{ms} through tuning of PI controller of rotor side voltage source converter. At this condition also maintain the total harmonics distortion in certain limit for Power quality improvement.

From the observation of the results it could be concluded that the vector control technique is more effective for constant voltage and frequency control operation at variable wind speed and load changes conditions for power quality improvement in real time applications.

5. Conclusion

In this paper the validation of the MATLAB simulation results are verified through OPAL RT real time implementation. In consideration of find the effectiveness Power Quality Improvement by using vector control technique in stator and rotor side voltage source converter controller for constant voltage and frequency operation of a DFIG based SWECS in MATLAB Simulink Model are presented in this paper. The result obtained confirms the fulfillment of the necessary condition as stated above by the proposed controller for real time application.

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