International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-12, October 2019

Rotor Power Flow Control of Doubly Fed Induction Generator using dSPACE ds1104

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Abstract*: *An RSC control of a DFIG connected to grid using controller objective dSPACE ds1104 is presented. A stator flux control vector scheme is exercised to control the both active & reactive powers produced at stator terminals by DFIG. Rotor excitation is given by using an appropriate SPWM pulse fed Inverter at rotor side achieved by changing modulation index & modulation frequency. For MI & MF SPWM pulses, dSPACE dS1104 is employed for real time control & generation. Updation of corresponding parameters in display are observed through Control Desk.

Keywords* : *DFIG, RSC, dSPACE, Modulation Index (MI), Modulation Frequency (MF)

I. INTRODUCTION

Nowadays, renewable energy-source systems are always the major subject of much recent research & development because of the problems associated with conventional sources. Observing the prevailing rate of energy intake at global scene, fossil fuels will soon deplete as they cannot replenish enough to meet growing demands. The high consumption of these fuels leads to greenhouse gases & pollutants into the air - causing atmosphere warming & climate crisis. As such government is forced to look for available alternative green sources like solar, wind, hydropower, geothermal, bioenergy etc. From those listed sustainable sources, the highly sought-after source which meets these entire requirements is wind-power and is infact one of the fastest-emerging renewable-energy technologies. Its worldwide usage is on rise, in part because costs are falling. And so, it has become-a viable solution for the generation of electrical-energy [1]. Even though most of the wind-turbines installed have a fixed speed, the number of wind turbines having variable speeds is increasing at a steady rate. Infact most emerging wind farms prefer to choose variable speeds wind turbine systems to overcome the problems associated with fixed-speed wind turbine systems and also its prospective in harvesting more wind energy.

Revised Manuscript Received on October 30, 2019.
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Doubly Fed InductionGenerator (DFIG) is one of the viable components of varying speed wind turbine systems. Overall advantages are more than what fixed speed generators offers which includes speed control. These merits are mainly achieved by controlling converter at rotor side. Countless works presented the behavioural study of grid-connected DFIG wind-turbine systems. Most existing models uses vector control as control scheme in Doubly Fed InductionGenerator. Stator to Grid connection is made directly while the rotor is fed to magnetize the machine.

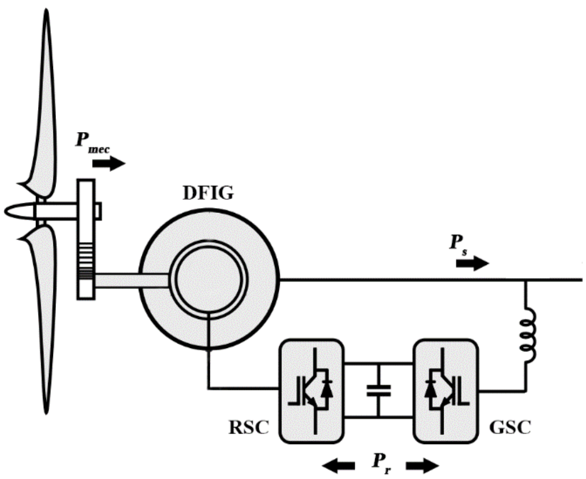

Fig1: A typical DFIG based wind energy conversion system

DFIG has more advantages in WECS system. The leading advantage is its ability of doubly-fed induction-generator to supply power both at leading & lagging power factors white the other one is ability to control rotor voltages and currents. This enables the DIFG to always remain in synchro with grid no matter what wind turbine speed is. In actuality, the main reason DFIGs are popular and widely preferred in wind power generation is due to their ability to supply power at constant voltage & frequency even at varying rotor speed, they are widely sought after. And in addition, rotor side control of DFIG is much more cost effective as the rotor side converters have to deal with comparatively less power than those grid side converters.

II. WIND TURBINE OVERVIEW

Wind turbines harnesses the spinning blades energy that can power a turbine by converting from kinetic to mechanical energy.

If the build-up harvested energy is used for generating electrical energy then it is called a wind turbine or wind-generator or wind-changer. If the very same harvested energy is instead used to drive machinery, then it is called an aerogenerator or wind-mill. Current wind-turbines are of two basic types based on their axis of rotation - Horizontal & Vertical. Wind turbines with horizontal axis of rotation normally have 2-3 blades are mainly operated "upwind", where blades are positioned into the wind. Generally normal turbines are used for applications such as water pumping, standalone systems for home, business & auxiliary power on naval boats etc. But such large turbines in clusters, or arrays connected to grid are becoming an alternative viable source of generating commercial electric power. Wind turbine operates on a basic principle that harnessed kinetic energy produced by blades is converted to mechanical and then finally to electrical energy via DFIG.

A. Modelling of Wind turbine

The wind turbine model simulation is subjected to sporadic variations in wind velocity consisting of gusts and ramp wind components[2]. The velocity of wind (V_{tw}) can be written as,

$V_{tw} = V_{bw} + V_{gw} + V_{rw}$

where,

V_{tw} = Tital wind velocity,

V_{bw} = Base wind velocity,

V_{gw} = Gust component &

V_{rw} = Ramp component of wind

The base wind speed is a constant & is given by,

$V_{bw} = C_1$; C_1 = constant

The gust component is represented as a (1-cosine) term & is given by,

$$V_{gw} = \begin{cases} 0 & t < T_1 \\ C_2\left\{1 - \cos\left[\pi \frac{t-Ta}{t-Tb}\right]\right\} & T_2 \le t \le T_1 \\ 0 & t \ge T_2 \end{cases}$$

C_2 - maximum of gust component. Ta & Tb are start & stop times of the gust.

Below equation shown is ramp function representing rapid wind speed variations,

$$V_{rw} = \begin{cases} 0 & t < T_3 \\ C_2\left\{\frac{t - T_3}{T_4 - T_3}\right\} & T_3 \le t \le T_4 \\ 0 & t \ge T_4 \end{cases}$$

where C_3 is the maximum change in wind speed caused by the ramp and T_3 & T_4 are the start and stop times of ramp, respectively.

In theory, the amount of wind power that is possible for extract or harvest by a wind turbine is around 58% of total power content of the wind, considering Betz limit. Typical value of turbine power constant is lower than 0.45. The equation of wind turbine model is given as

$$J_s \frac{dw_r}{dt} + B_s w_r = T_m - T_e$$

where in,

J_s - Shafts Total Inertia,

B_s - Coefficient of friction,

T_m - Wind torque

T_e - Generator electromagnetic torque

The generated torque is then given by

$$T_m = \frac{P_m}{w_r}$$

According to Betz the maximum wind turbine power output,

$$P_m = \frac{16}{27} A_r \frac{\rho}{2} V_1{}^3$$

is obtained when, $V_2 = 2/3\ V_1$ & $V_3 = 1/3\ V_1$
where,

V_1 = Undistributed far-upstream wind speed,
V_2 = Wind speed at turbine,
V_3 = Decelerated wind far-downstream turbine,

The turbine model represents the harnessed power by the turbine.

$$P_w = \frac{1}{2}\rho A V_w{}^3, A_r = A$$

where, V_w is the velocity of wind.

Even so, the turbine is only able to conserve a fraction of this power. This harnessed power by the turbine (Pm) can be written as show below,

$$P_m = P_w \ x\ C_p$$

where C_p is a fraction called the power coefficient. It represents how much fraction of power the turbine model harnessed from the wind & it has a theoretical 0.55 max value.

This coefficient in its empirical form is as shown below

$$C_p = \frac{1}{2}(\gamma - 0.022\beta^2 - 5.6)e^{-0.17\gamma}$$

β - blade pitch angle,
γ - tip-speed ratio of turbine,

$$\gamma = \frac{v_{w\,(mph)}}{\omega_{b\,(rad\ s^{-1})}}$$

Where, (ω_b = angular speed)

B. *Modelling & Analysis of the DFIG*

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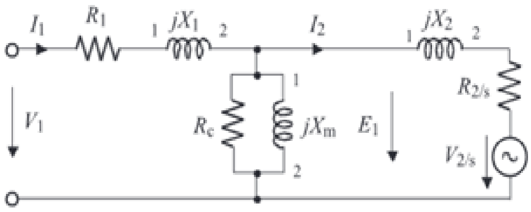


Fig2: Equivalent circuit of DFIG

Doubly-fed induction generator used is a standard wound-rotor IG where its windings are connected in grid to back-back converters and then to rotor. The DFIGs operation can be explained using classic rotating fields theory and well-known d-q model, as well as both three-to-two and two-to-three axes transformations.

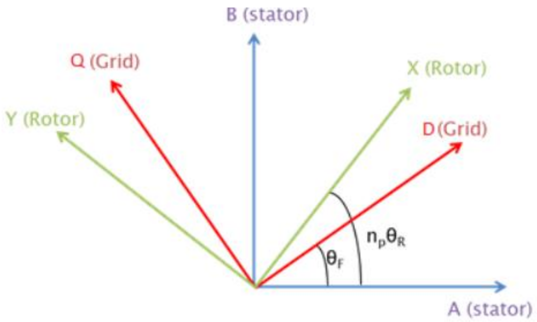


Fig3: Vector Diagram showing transformations

The following equations represents the typical dynamic modelling of DFIG in synchronous rotating reference frame d_e-q_e

$$V_{ds} = R_s I_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs}$$
$$V_{qs} = R_s I_{ds} + \frac{d\psi_{qs}}{dt} - \omega_s \psi_{ds}$$
$$V_{dr} = R_r I_{qr} + \frac{d\psi_{dr}}{dt} - (\omega_s - \omega)\psi_{qr}$$
$$V_{qr} = R_r I_{qr} + \frac{d\psi_{qr}}{dt} - (\omega_s - \omega)\psi_{qr}$$

The stator & rotor fluxes can be expressed as

$$\psi_{ds} = L_s I_{ds} + M I_{dr}$$
$$\psi_{qs} = L_s I_{qs} + M I_{qr}$$
$$\psi_{dr} = L_r I_{dr} + M I_{ds}$$
$$\psi_{qr} = L_r I_{qr} + M I_{qs}$$

where,

$L_s = l_s - M_s$ - At stator side, both cyclical & mutual cyclical inductance

$L_r = l_r - M_r$ - Similarly at rotor side, both cyclical and mutual inductance.

M is the max mutual cyclical inductance.

Its electromagnetic torque is given by

$$T_{em} = p.(\psi_{ds}.I_{qs} - \psi_{qs}.I_{ds})$$

Where p being no of pole pairs.

The stator's and rotor's active & reactive powers can be written as shown below

$$P_s = v_{ds}.I_{ds} + v_{qs}.I_{qs}$$
$$Q_s = v_{qs}.I_{ds} - v_{qs}.I_{qs}$$
$$P_r = v_{dr}.I_{dsr} + v_{qr}.I_{qr}$$
$$Q_r = v_{qr}.I_{dr} - v_{dr}.I_{qr}$$

C. *Vector Control of the DFIG*

Two different controlling approaches are listed below, they are:

a. Closed loop flux control, where frequency and voltages are considered variables (unstable network).

b. Open loop flux where frequency and voltages are constant (stable network).

In this study, frequency and voltage is considered to be constant. Seeing the equation, it is evident that there is a strong coupling between fluxes and currents [5]. In addition, the DFIG controlling becomes difficult due to the electromagnetic torque being a direct cross product of flux & stator currents. For easier control rein, DC machine model is used due to its decoupling nature between stator currents and flux. In order to achieve this, we use vector control approach. A two-phase d_q reference linked to the rotating field is chosen. Along d-axis stator flux Ψ_s is oriented. Thus, we can write:

$$\psi_{ds} = \psi_s$$
$$\psi_{qs} = 0$$
$$\psi_{ds} = L_s i_{ds} + M i_{dr} = \psi_s$$
$$\psi_{qs} = L_s i_{qs} + M i_{qr} = 0$$
$$i_{ds} = \frac{\psi_s}{\psi_s} - M i_{dr}$$
$$i_{qs} = -\frac{M}{L_s} i_{qr}$$

The electromagnetic torque then becomes:

$$T_{em} = -P\frac{M}{L_s}\psi_s.I_{qr}$$

In WECS systems, mainly medium & high-power machines are preferred. As a result, stator resistance is neglected. If stator flux is a constant, then we can write,

$$V_s = 0$$
$$V_{qs} = V_s = \psi_s.\omega_s$$

V_s is line voltage. From torque equation, it is evident that by controlling quadrature rotor current (i_{qr}), control of electromagnetic torque of DFIG can be done.

Using vector control approach of DFIG we can write power equations as

$$P_s = v_{qs} I_{qs} = -\frac{M}{L_s} V_s I_{qr}$$
$$Q_s = v_{qs}.I_{ds} = V_s(\frac{\psi_s}{L_s} - \frac{M}{L_s} I_{dr})$$
$$P_r = v_{dr} I_{dsr} + v_{qr} I_{qr}$$
$$Q_r = v_{qr} I_{dr} - v_{dr} I_{qr}$$

Finally, active and reactive powers can be rewritten as below

$$P_s = -\frac{M}{L_s} V_s I_{qr}$$
$$Q_s = V_s(\frac{\psi_s}{L_s} - \frac{M}{L_s} I_{dr})$$

$$P_r = g\frac{M}{L_s}V_s I_{qr}$$
$$Q_r = g\frac{M}{L_s}V_s I_{dr}$$

III. DFIG RSC CONTROL SCHEME

Extensive research has been done and with regards to decoupling active and reactive power. First vector control scheme is proposed by F. Blaschke. Not only PI controllers, but also fuzzy controllers, sliding mode controller etc are used in this scheme for active & reactive power control.

Out of those controllers, PI is widely chosen for its simplicity and easy adaptability. Since stator of DFIG is directly coupled to grid, stator voltage magnitude and frequency can be approximated to be constant. So stator flux oriented control method is normally adopted. WECS systems using DFIG needs control of voltage source converter to achieve variable speed operation.

A. Rotor Side Converter Control

In this vector control, P and Q variables are controlled using RS converter. Stator flux control approach is used. Direct-axis and Quadrature-axis are respectively used for reactive & active power control.

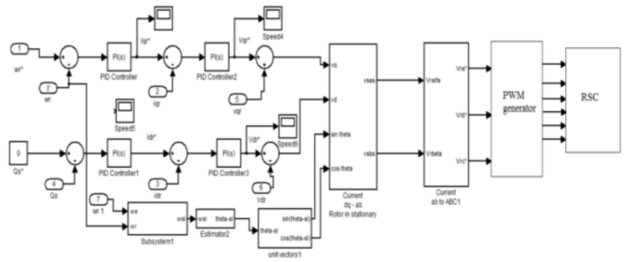


Fig4: RSC pulses simulation in simulink

$$V_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dx} - \omega_{sl}\sigma L_r i_{qr}$$
$$V_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dx} - \omega_{sl}\sigma L_r i_{dr} + L_o i_{ms}$$

B. Control of back-to-back converters

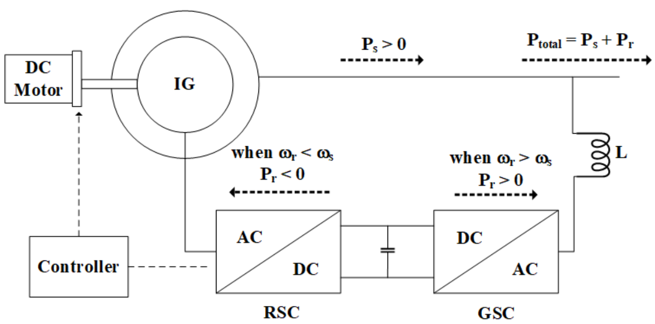


Fig:5 – Overview of RSC and GSC converters

The figure shows the general control block diagram of DFIG with converters at rotor and grid side. This is configured to operate at constant-frequency and variable-speed. An ac-dc-ac converter has been utilized for exchange of the power to dc link voltage, 3-ϕ rotor side converter and grid side converter with a common dc-coupling. The RSC and GSC regulates the power through the DC-link.

C. dSPACE Controller

dSPACE full name is digital signal processer for applied voltage engineering. This is best suitable for industrial automation. dSPACE is well appropriate for drive control and the cost is effective. DSPACE is real time processor and it is source open software application that allows to capture and store. It provides a RTI based control through its proprietary software control desk. It provides predefined set of control blocks which can be easily interlinked to MATLAB Simulink. It provides access to the input and output pins on dSPACE hardware. Implementation time is greatly reduced as it handles any continuous time, discrete time depending upon the input and output of hardware and different subsystems. It offers check interrupts that helps avoiding double or improper use of channels.

This is installed in desktop. MATLAB files is interfaced through dSPACE package software. It can operate up to 250mhz. 2k frequency pulse width is generated and also it consists of 8 analog and 8 digital pins. DS1104 r&d board is mainly used in research experiments in institutional labs.

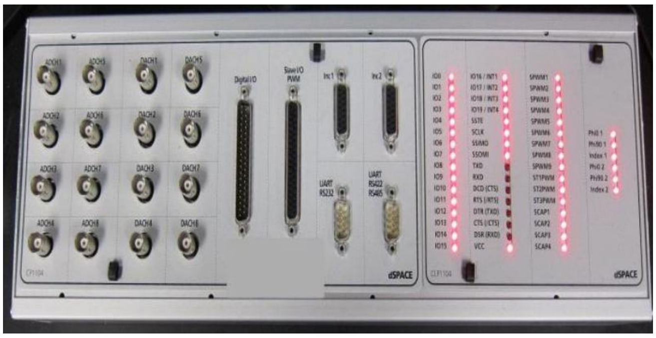


Fig:6 – dSPACE ds1104 Controller

D. Voltage Sensor

A voltage sensing circuit as shown in below fig is similarly used for the generation of a reference signal with the help of PLL (Phased Locked Loop) for which suitable PWM pulses are applied using Sinusoid PWM control strategy.

Fig:7 – Voltage sensor

E. Phase Locked Loop

PLL used is a linear-feedback controlling system which can be used-to generate a reference signal for the dSPACE having similar frequency & phase of grid signal. Here grid signal is used as input for generating reference signal.

In general, PLL model is used for synchronization of closed loop controlling and for recovering noiseless communication and generation of stable frequency for digital circuits.

F. QEP Sensor

A Screw mount style Quadrature encoder pulse of 512 PPR is employed on the DFIG rotor shaft as shown in below fig for the generation of index pulses which are used in the calculation of theta angle using appropriate DFIG-system blocks in MATLAB.

Fig:8 – QEP sensor mounted on DFIG rotor shaft

IV. OVERVIEW OF HARDWARE

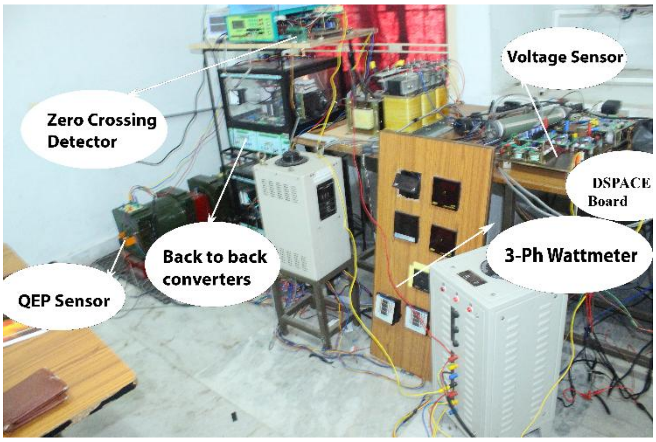


Fig:9– DSPACE controller with IM kit

V. SIMULATION

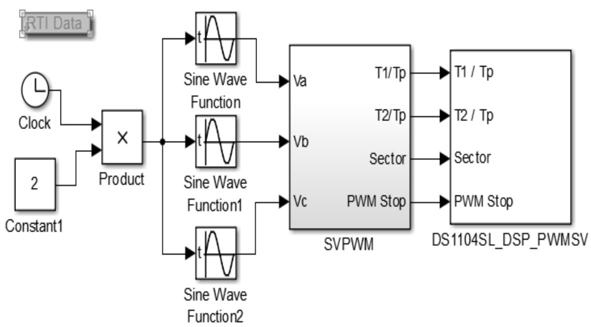


Fig10: SVPWM generation block through dSPACE block

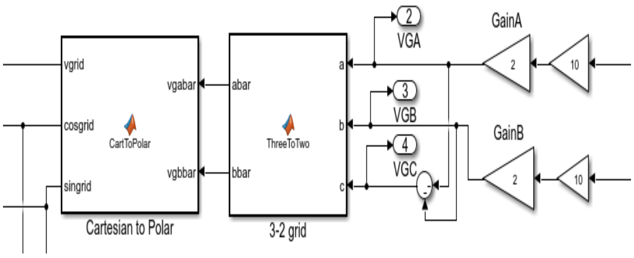


Fig11: Reference signal generation using grid signals

The above figure-11 takes grid signals as input from voltage sensor. It is interfaced to dSPACE through an ADC pin and similarly a DAC is used for real-time-viewing of generated reference signal.

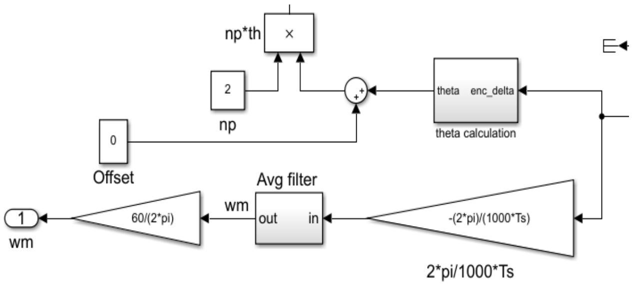
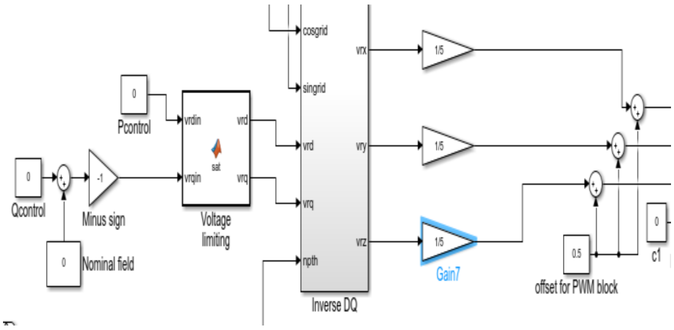


Fig12: Encoder block for QEP sensor

The above figure - 12 shows an encoder block that takes an input from QEP sensor. This is used to estimate index pulses and finally RPM of DFIG



.Fig13: RSC control block for generating control pulses to DFIG

The above figure - 13 is used for control of P and Q parameters such that desired results are obtained and correspondingly suitable pulses are fed to dSPACE PWM block.

VI. HARDWARE RESULTS

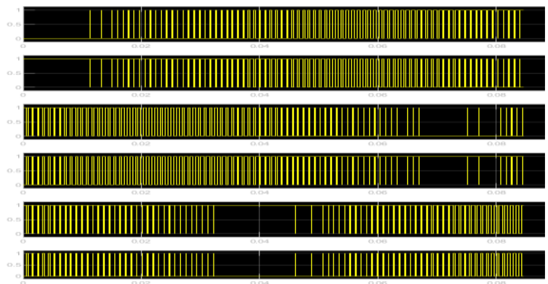


Fig14: Gate pulses

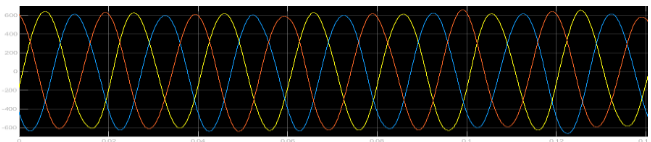


Fig15: O/p line voltages (Stator)

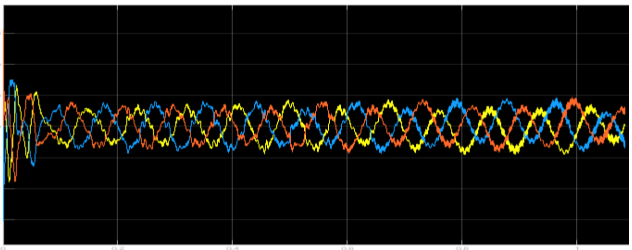


Fig:16 Rotor voltages

Fig17: Stator voltage, Active power, and RPM

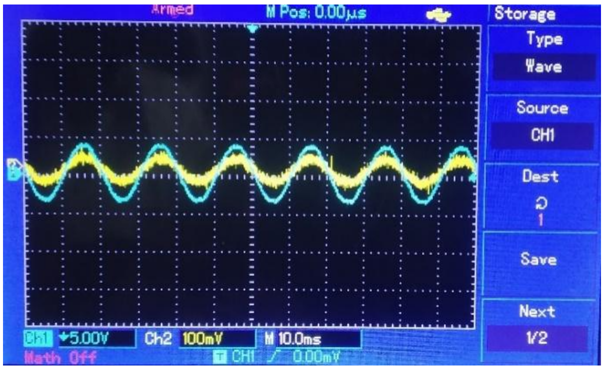


Fig17: Output voltage maintained constant irrespective of wind speed (rotor speed)

Table1: DC link voltage, Stator Voltage, RPM and Active power

S.NO	DC Link Voltage	Stator Voltage	(RPM)	Stator Active power (KW)
1	150	108.5	1256	0.091
2	150	109.6	1326	0.093
3	150	109.8	1423	0.073
4	150	110.0	1456	0.085
5	150	112.0	1499	0.065

VII. CONCLUSION

In brief, a vector control algorithm in RSC controller is implemented in hardware and its performance is validated in real time in ControlDesk. A signal conditioning circuit is used for voltage & current measurement for RSC operation. The obtained results are analysed at different speeds by manually varying the motor speed (WT speed). This operation uses sinusoidal-PWM for generating RSC converter-pulses. Finally, a detailed analysis of experimental results has been laid out to show the effectiveness of the proposed controller with DC-machine coupled with induction machine-fed with GSC & RSC back-to-back converter.

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