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Comparative Analysis of Direct Power Control (DPC) and Direct Voltage Control (DVC) for Control of Doubly Fed Induction Generator (DFIG) Connected to a Variable Speed Wind Turbine

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ABSTRACT

A relative study of two control strategies for the control of Doubly Fed Induction Generator (DFIG) attached to a variable speed wind turbine is carried out in this paper. Control1 uses direct power control (DPC) strategy which involves control of active and reactive power. The results indicate that active and reactive power follows the corresponding reference values at different operating conditions. In control2, the modified direct voltage control (DVC) scheme is used for control of RSC. The supply side converter is given with vector voltage control. The comparative analysis is carried out by using MATLAB/SIMULINK model of the system. Also THD analysis is done for the obtained results.

Index terms: doubly fed induction generator (DFIG), Direct voltage control (DVC), Direct power control (DPC), wind energy conversion system (WECS), grid side converter (GSC), rotor side converter (RSC).

II. INTRODUCTION

Among the renewable resources available, wind energy seems to have developed the most. Among many research works carried to extract maximum energy, using a DFIG connected to wind turbine system is one of the popular techniques inculcated to increase the efficiency, improve the power rating, and reduce the cost so as to make the overall system effective. The variable speed wind operation yields an increase in the total energy production [1]. The system consists of the wind turbine with various speeds attached to DFIG. The rotor is connected to back to back converter system and stator is connected along with the grid. Various control strategies are used for the control of converter. DPC and modified DVC are the two techniques used here for the RSC where the GSC uses vector voltage control technique. The slip power is taken or given back in super or sub synchronous mode respectively to the rotor in order to maintain constant speed operation thus allowing maximum extraction of energy [9].

III. MODEL OF WIND TURBINE

The power (maximum) that can be obtained from the wind as per the conservation of mass and energy principle is found to be

$$P_{maximum} = (8/27)*\rho*A*V_{„}^{3} = (16/27)*P_{mechanical} \quad (1)$$

Theoretically power extractable (maximum) from the wind is 0.593 times that of the present power. The wind power in terms of kinetic energy of the air flow mass per unit time is given as

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$$P_{mechanical} = (1/2)*\rho*A*V_{\infty}^{3}*C_P \quad (2)$$

Where, ρ is the air density given in (Kg.m^3), C_p is power coefficient), A is area of rotor (A=π*R^2 given in m^2),V_∞ being the wind velocity (given in m^2/s), tip speed ratio (λ), pitch angle of blade (β), w_r is the angular speed of turbine shaft and R_{rot} is the rotor blade radius [8].

$$\lambda = (w_r * R_{rot})/v_w, \lambda_i = \frac{1}{\left(\frac{1}{\lambda} - 0.02\beta\right)\left(0.003/1 + (\beta*\beta*\beta\right)} \quad (3)$$

$$C_p = (73/100)*\left(\left(\frac{151}{\lambda i}\right) - 0.58*\beta - 0.002\beta^{2.14} - (132/100)\right)*e\frac{-13.4}{\lambda i} \quad (4)$$

The power coefficient of the wind energy is given by C_p = output power from wind turbine divided by power contained in the wind

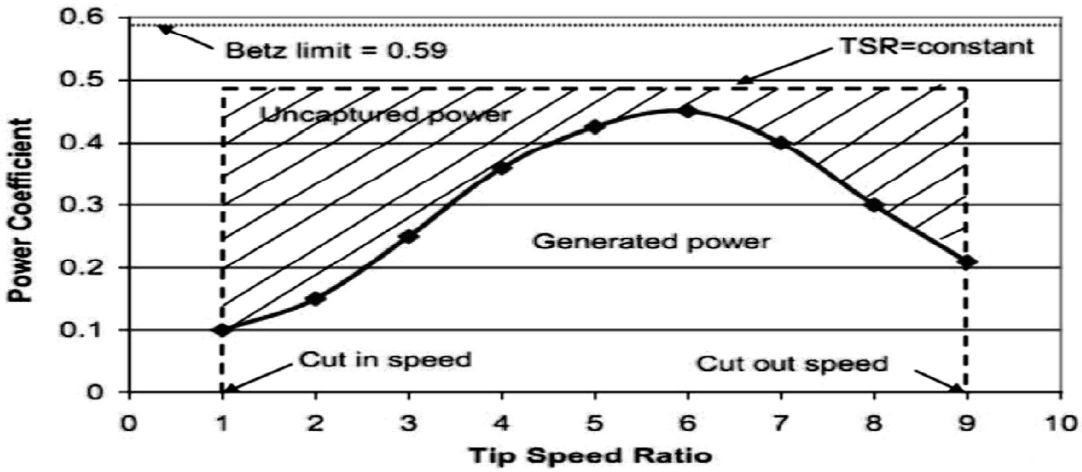

Figure 1: Power coefficient Vs Tip speed ratio

IV. STRUCTURE OF DFIG

Doubly fed induction generator is a wound rotor machine where stator and rotor both are attached to electrical sources. The stator windings are directly fed from a three phase 50-Hz AC source. In DFIG, the rotor is connected to the grid by means of electronic interface consisting of GSC and RSC convertors

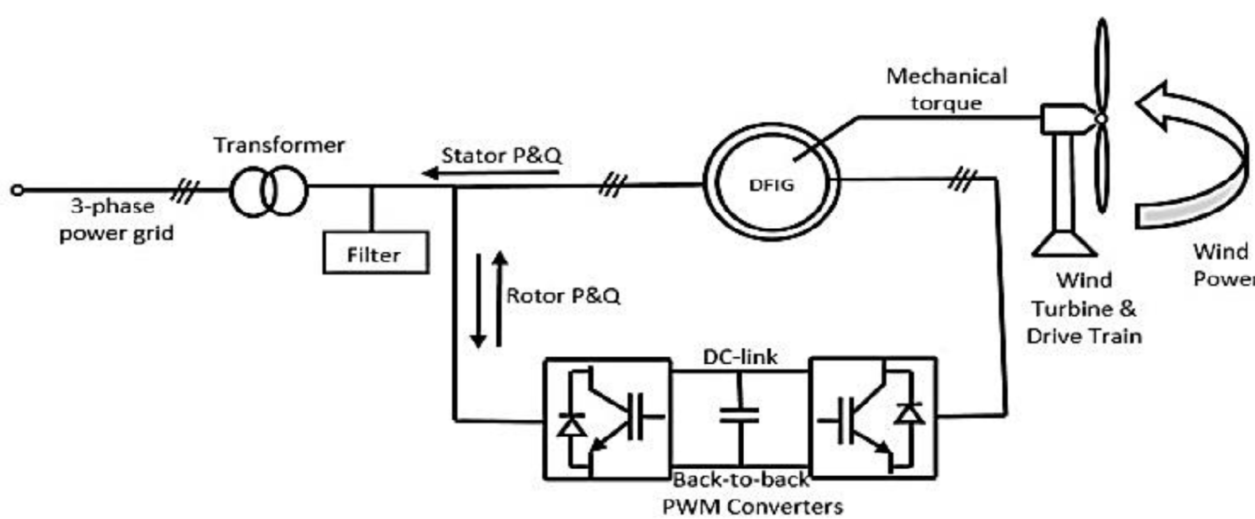

Figure 2: Block diagram of DFIG connected to WECS [10]

(IGBT based back to back PWM convertors) at a variable frequency via a DC-link capacitor. GSC and RSC side convertors are controlled by different control strategies where DVC is employed at the GSC side and a comparison is drawn between DPC and modified DVC employed at the RSC side. The primary aim of the recommended control technique is to regulate the voltage as well as frequency constant.

The DFIG rotor with variable speed capability can typically operate in three different modes. The different modes are sub-synchronous, synchronous and super-synchronous modes of operation. The slip power recovered from rotor can be effectively and efficiently transferred in dual directions with respect to the speed (operating) of the rotor. In case of super synchronous mode of operation, $P_{mechanical} = P_{r*}(1+s)$. In case of sub synchronous mode of operation, $P_{mechanical} = P_{r*}(1-s)$

V. GRID SIDE AND ROTOR SIDE CONVERTER'S CONTROL STRATEGIES

The DFIG's control is inevitable and unavoidable for an appropriate energy conversion. It's vital to maintain the magnitudes of torque, speed, active, reactive power and the dc link capacitor voltage nearer to their optimal values. Two control strategies are discussed: One is the Direct Power Control and other is the Direct Voltage Control technique. Finally results are computed at the GSC side and also for the RSC side involving two control strategies.

(A) GRID SIDE CONTROL (Vector control)

The stator flux oriented vector technique shown in Fig. 4 is adapted to regulate the grid side convertor of DFIG. The active and reactive power transfer amidst the grid side and the stator side convertor is controlled independently through stator- flux oriented vector scheme. The main purpose of the grid side convertor is to preserve the dc link voltage (capacitor voltage) constant without taking into account the rotor's power flow directions [5]. A PWM scheme with d-q axis current (direct and quadrature axis) which is current controlled is used for the control and regulation of both dc capacitor voltage as well as reactive power.

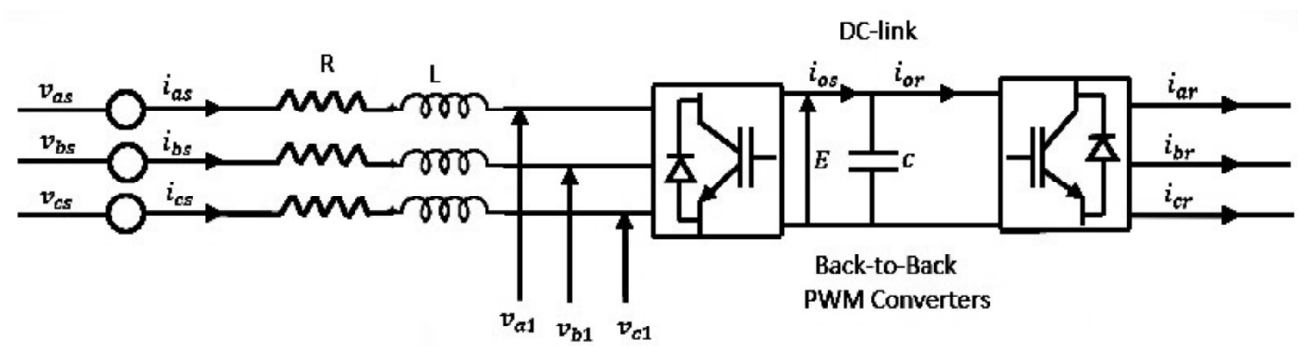

Figure 3: Structure of connection between Grid and back-to-back PWM converters [2]

$$\begin{bmatrix} v_{astat} \\ v_{bstat} \\ v_{cstat} \end{bmatrix} = R * \begin{bmatrix} i_{astat} \\ i_{bstat} \\ i_{cstat} \end{bmatrix} + L\rho * \begin{bmatrix} i_{astat} \\ i_{bstat} \\ i_{cstat} \end{bmatrix} + \begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{bmatrix} \tag{5}$$

The above eq. is articulated using phase, rotation transformations:

$$V_{dstat} = R*i_{dstat} + L\rho*i_{dstat} - w_{e*}L*i_{qstat} + V_{d1} \tag{6}$$

$$V_{qstat} = R*i_{qstat} + L\rho*i_{qstat} - w_{e*}L*i_{dstat} + V_{q1} \tag{7}$$

The supply flux angle can be obtained as:

$$\theta_e = \int w_e\, dt = a\tan\frac{v_\beta}{v_\alpha} \tag{8}$$

V_{qstat}= 0, as d-axis is found to align along the stator-voltage. Also V_{dstat} is considered constant due to constant supply voltage,

$$P_{stat} = 1.5*V_{dstat}*i_{dstat} Q_{stat} = -1.5*V_{ds}*i_{ds} \tag{9}$$

The voltage, current equations below are taken as per [6]

$$Ei_{os} = 3*V_d*i_d,\ V_d = (m_1*E/2*1.414) \tag{10}$$

$$i_{os} = (3*m_1*i_d/2*1.414),\ C\frac{dE}{dt} = (i_{os} - i_{or}) \tag{11}$$

i_d controls the dc link voltage.

$$V_{d1}^* = [\ -V_d' + (w_s L i_q + V_d)] = [-V_d' + V_{d1}^{comp}] \tag{12}$$

$$V_{q1}^* = [-V_q' + (w_s L i_d\ )] = [-V_q' + V_{q1}^{comp}] \tag{13}$$

V_{d1}^* and V_{q1}^* are taken as the reference for the GSC. V_{d1}^{comp} and V_{q1}^{comp} are used to depict the voltage compensation. Thus, independent control of dq axis components is achieved by this method. The leakage inductance change will drastically impose changes in the estimated rotor flux in direct rotor flux oriented strategy. Stator flux estimation is proved to be better and thus incorporated in the supply side converter's control strategy which is instrumental in maintaining the dc link voltage constant.

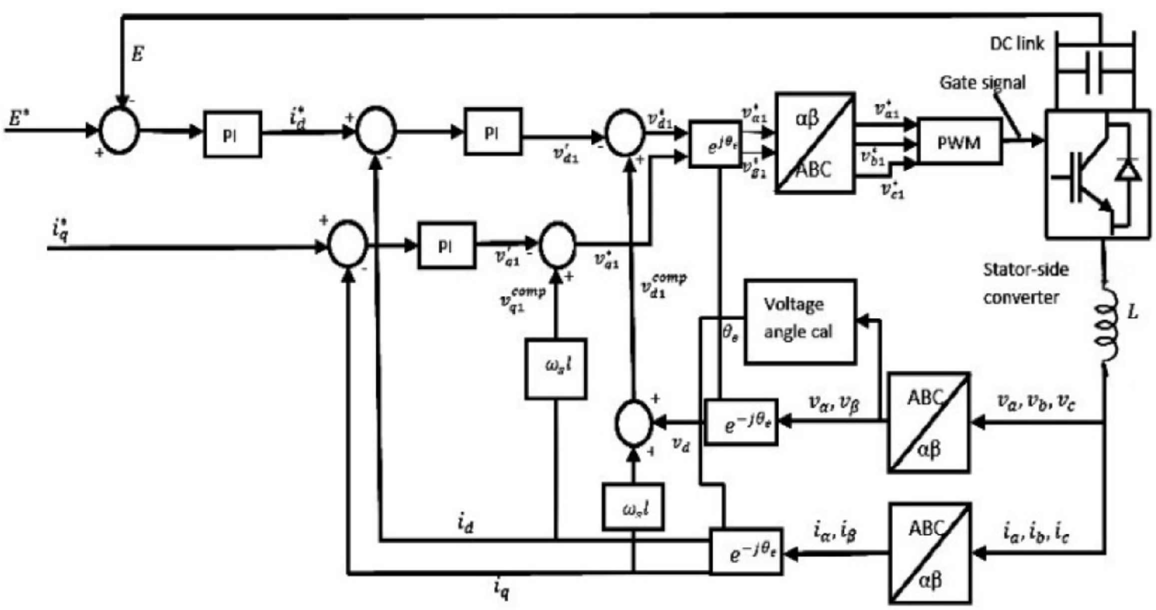

Figure 4: Block Diagram depicting Stator Side Converter Control Scheme [4]

A. ROTOR SIDE CONTROL

Control 1: Direct Power Control (DPC)

The block diagram portraying DPC at RSC is shown in Fig.5. Grid and stator voltages (v_{ga}, v_{gb}, v_{gc}), (v_{sa}, v_{sb}, v_{sc}), stator and rotor currents, (i_{sa}, i_{sb}, i_{sc}), (i_{ra}, i_{rb}, i_{rc}) are measured to implement DPC. All the measured signals are altered to dq reference frame signals (voltage and current) since a rotating reference axis in used as a means to control the DFIG [3]. This technique lets an optimal independent control of d, q axes currents. Here f denotes quantity (either current or voltage) and grid voltage position is given by θ. The conversion from (d-q) axis to (α-β) axis is also essential in the control action (during and after).This transformation can be acquired by utilizing the inverse Park transformation as depicted by the below matrix.

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_{sl} & -\sin\theta_{sl} \\ \sin\theta_{sl} & \cos\theta_{sl} \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{14}$$

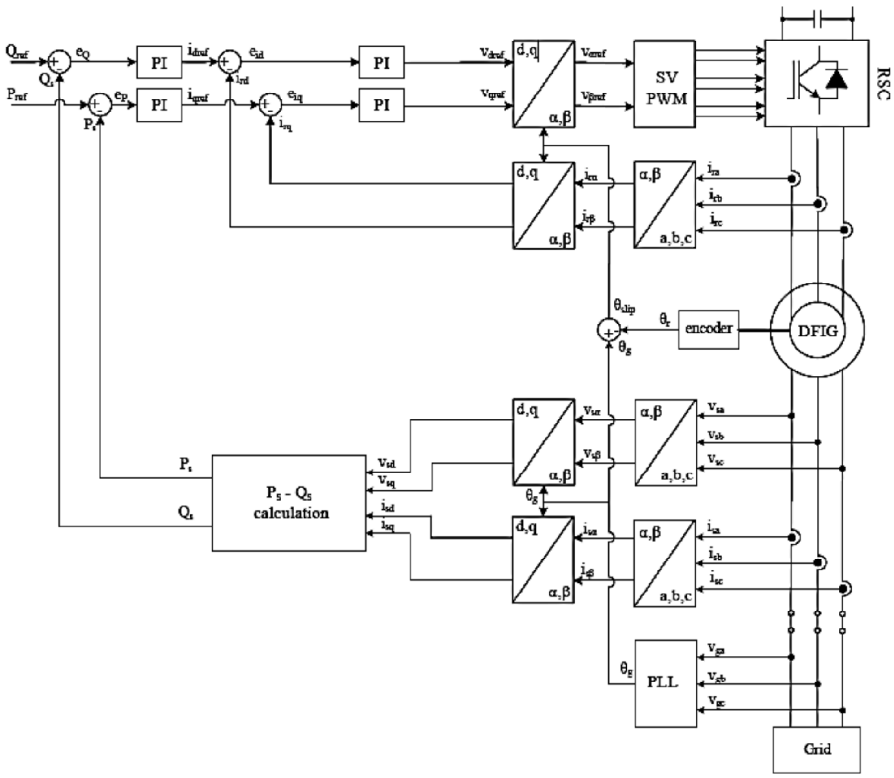

Figure 5: Rotor Side Converter Control Scheme [3]

The d-q frame reference currents i_{dref}, i_{qref} are acquired by measuring the active and reactive power errors amidst the reference and calculated values which are minimized by using PI controllers [7]. The received current values are then contrasted with the rotor currents and the corresponding errors are regulated by appropriate PI controllers and as a result voltage references are generated in d-q frame V_{dref}, V_{qref}. These voltage signals are converted to α-β-axis components ($V_{\alpha ref}$, $V_{\beta ref}$) by applying the inverse park transformation and then given to PWM block to attain the necessary switching signals for RSC of DFIG.

Control 2: Modified Direct Voltage Control (DVC)

DFIG voltages are regulated by stator flux oriented vector control scheme and by direct voltage control method. The simplicity of RSC is enhanced in the modified DVC compared to the complexity in the stator flux oriented vector control. The technique of DVC is regarded simple as it is devoid of rotor speed or position angle computation and due to the representation of voltage vectors (stator) in rotating reference. The reference frame rotates with ω^*_s synchronous speed reference corresponding to the stator voltage's reference frequency (generated). Voltage vector magnitude (constant) $|v_s|$ and the position angle θ_s referred to the d axis rotating frame is obtained from constant frequency as well as amplitude of the sinusoidal stator voltage (three phase) and from the consistent d-q stator voltage vector components [5]. The rotor current's magnitude and frequency is fed to the PI controllers (stator voltage). The sinusoidal voltage in three phase (vector form) in the rotating frame of reference is given as:

$$v_s = v_{dstat} + jv_{qstat} \quad (15)$$

$$|v_s| = \sqrt{v_{dstat^2} + v_{qstat^2}}.\theta_s = a\tan\left(\frac{v_{qstat}}{v_{dstat}}\right) \quad (16)$$

Thus, the stator voltage vector components (in (d,q) form) are based on:

$$v_{dstat} = (0.667)*[v_{as}\cos(w_{stat}*t) + v_{bs}\cos(w_{stat}*t - (2\pi/3)) + v_{cs}\cos(w_{stat}*t + (2\pi/3))] \quad (17)$$

$$v_{dstat} = (0.667)*[v_{as}\sin(w_{stat}*t) + v_{bs}\sin(w_{stat}*t - (2\pi/3)) + v_{cs}\sin(w_{stat}*t+(2\pi/3))] \quad (18)$$

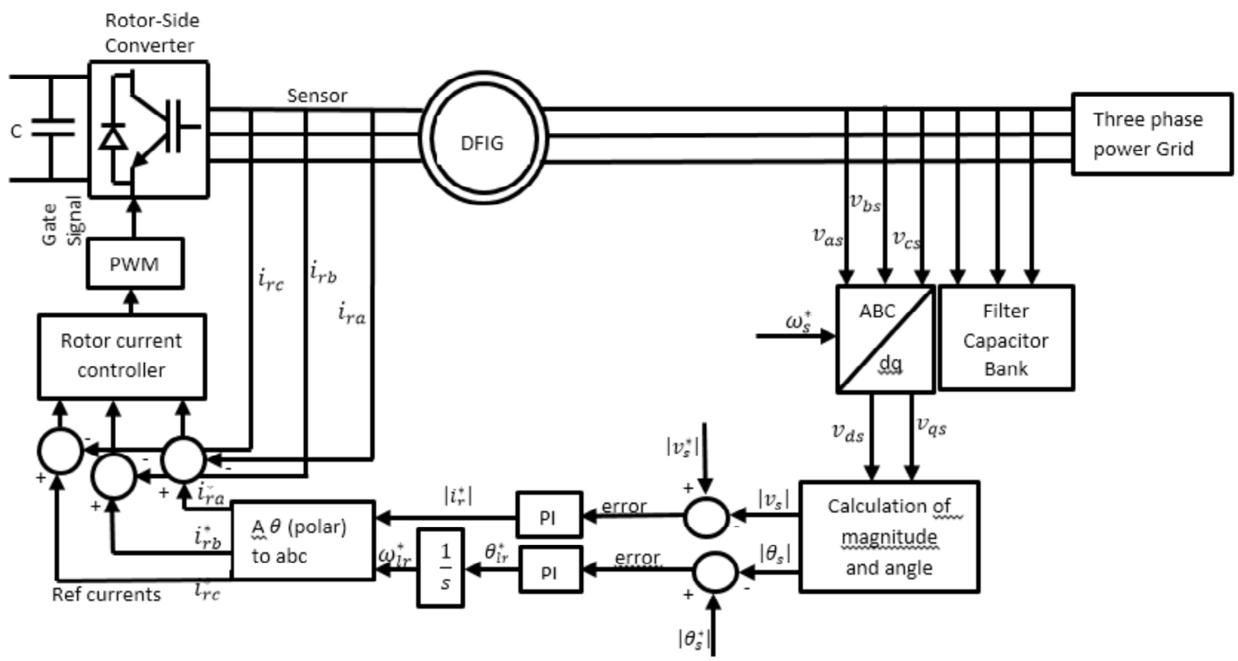

Figure 6: Modified DVC control scheme of rotor side converter [4]

The PI controller (first one) acts as a voltage manager on the basis of $|v_s^*|$ (reference stator voltage amplitude) and $|v_s|$ (actual stator voltage amplitude) and $|i_r^*|$ (the reference rotor current vector) amplitude is obtained. The PI controller (second one) acts as a frequency regulator with respect to reference position angle θ_s^* (stator voltage) and the actual position angle (stator voltage) θ_s and creates the reference angular speed (rotor current)$|\omega_{lr}^*|$. The reference vector position angle (rotor current) θ_{ir}^* based on rotor can be given as

$$\theta_{ir}^* = \int w_{ir}^* dt \quad (19)$$

The rotor current signal (three phase) (i_{ra}^*, i_{rb}^*, i_{rc}^*)for rotor current managers can be achieved utilizing the Polar to Cartesian conversion (A, θ) to (a, b, c) referred to the rotor[10].

$$\begin{bmatrix} i_{ra}^* \\ i_{rb}^* \\ i_{rc}^* \end{bmatrix} = |i_r^*| * \cos\begin{bmatrix} \theta_{ir}^* \\ \theta_{ir}^* - \frac{2\pi}{3} \\ \theta_{ir}^* + \frac{2\pi}{3} \end{bmatrix} \quad (20)$$

VI. SIMULATION RESULTS

Simulation results shows the comparative studies between DVC and DPC methods.

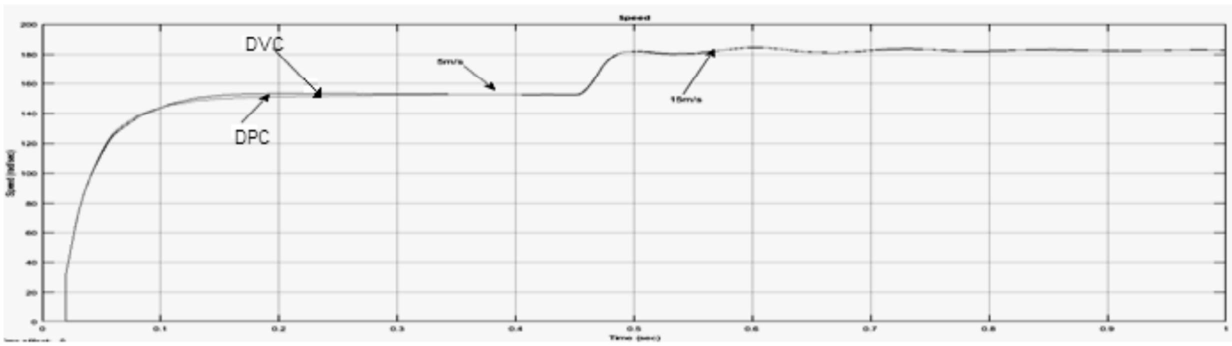

Figure 7: Rotor speed ω_m(rad/sec) characteristic for DPC and DVC

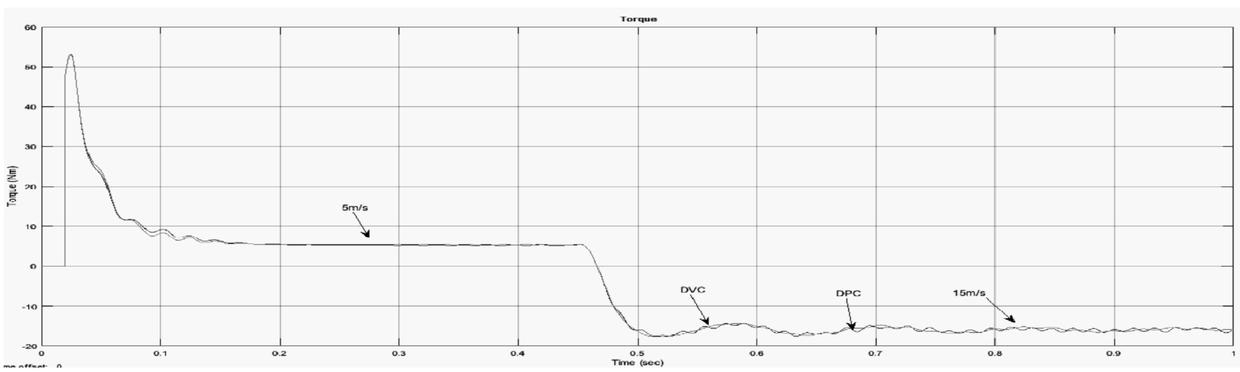

Figure 8: Rotor torque (Nm) characteristic for DPC and DVC

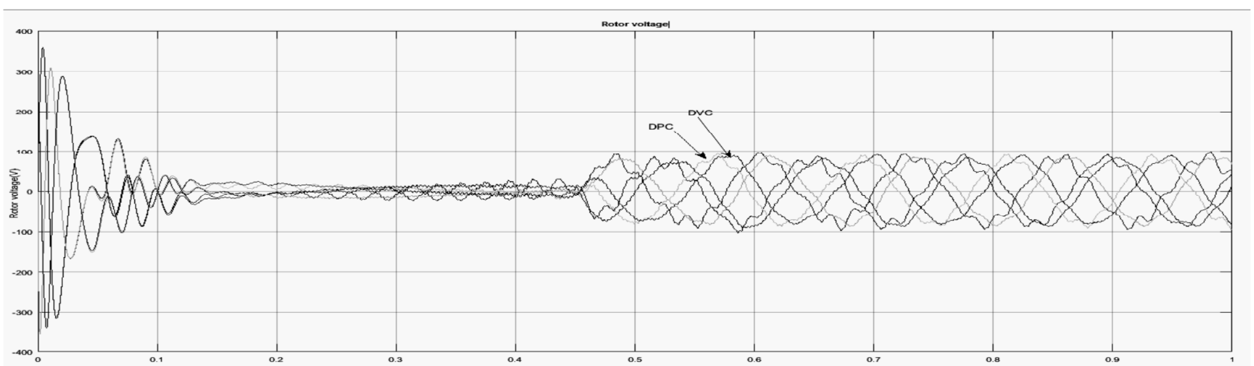

Figure 9: Rotor Voltages for DPC and DVC

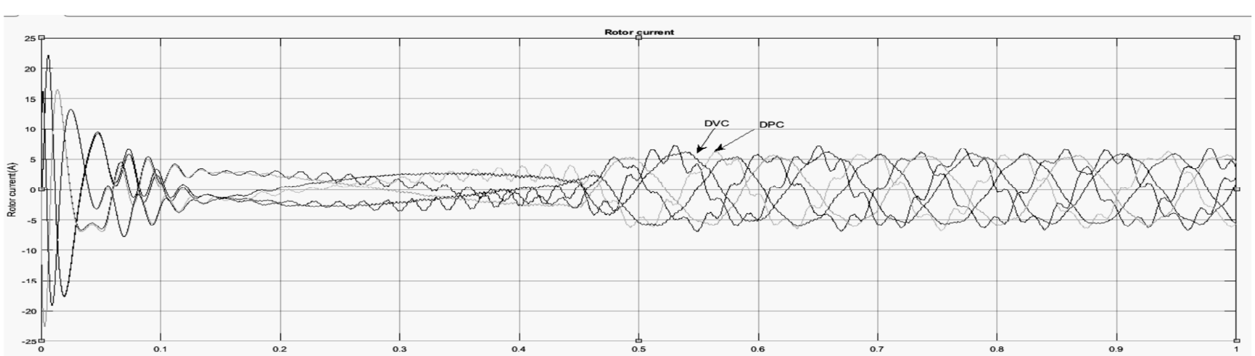

Figure 10: Rotor current for DPC and DVC

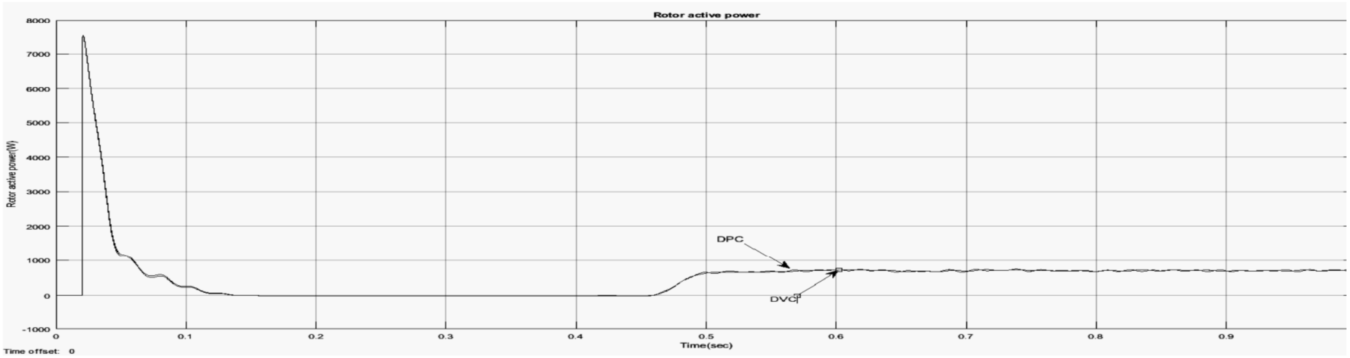

Figure 11: Rotor active power for DPC and DVC

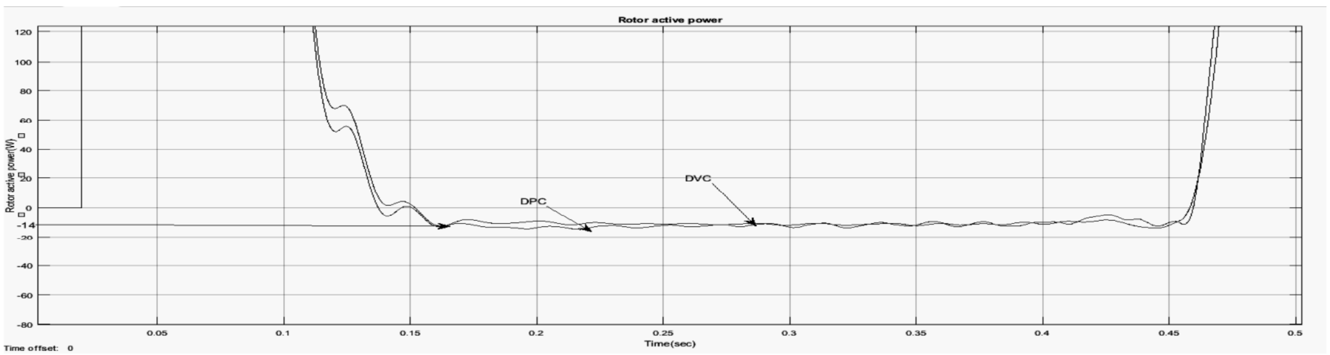

Figure 12: Rotor active power for DPC and DVC

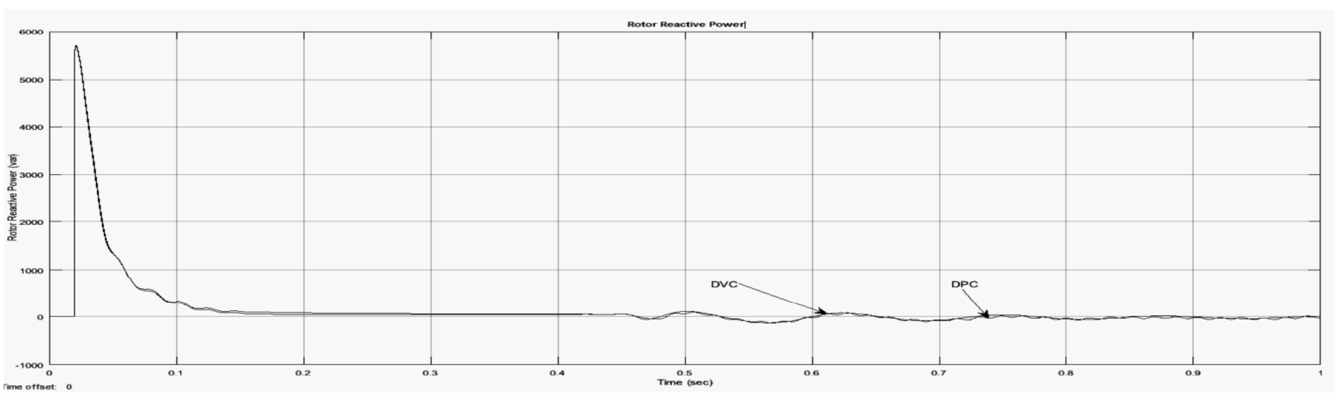

Figure 13: Rotor reactive power for DPC and DVC

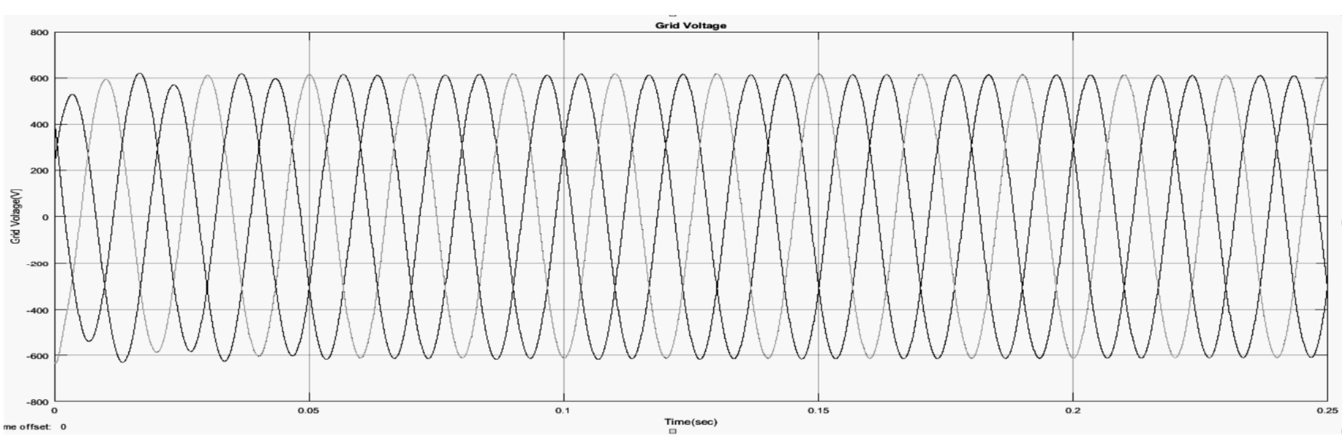

Figure 14: Grid Voltages for DPC and DVC

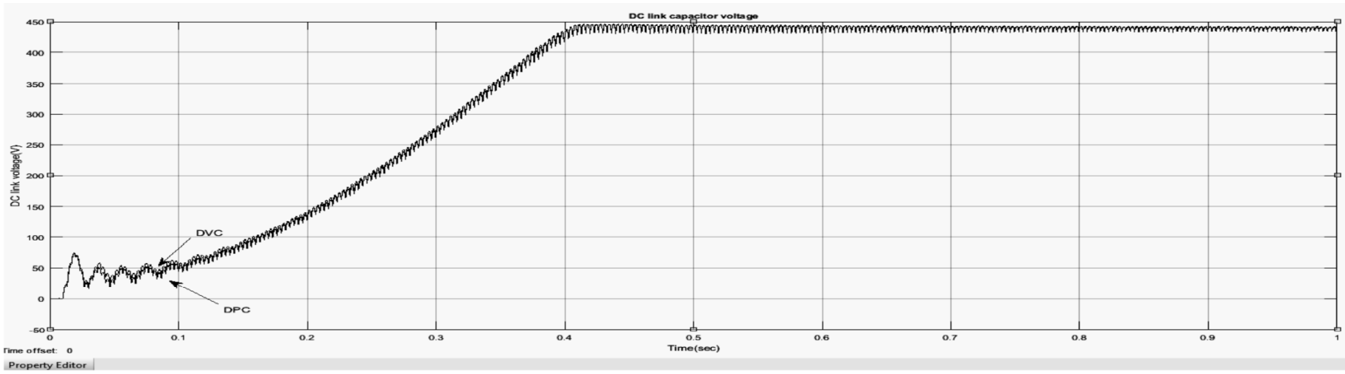

Figure 15: DC link capacitor voltage for DPC and DVC

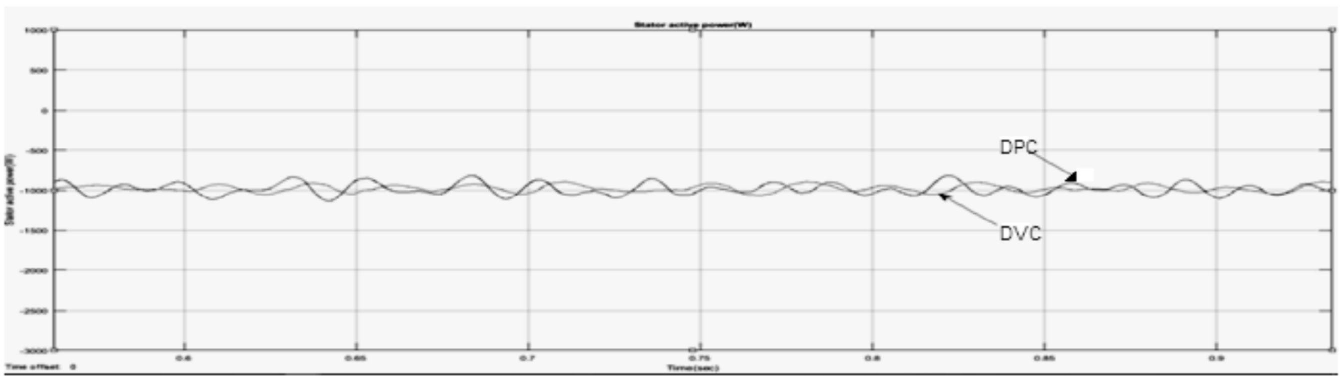

Figure 16: Stator active power for DPC and DVC

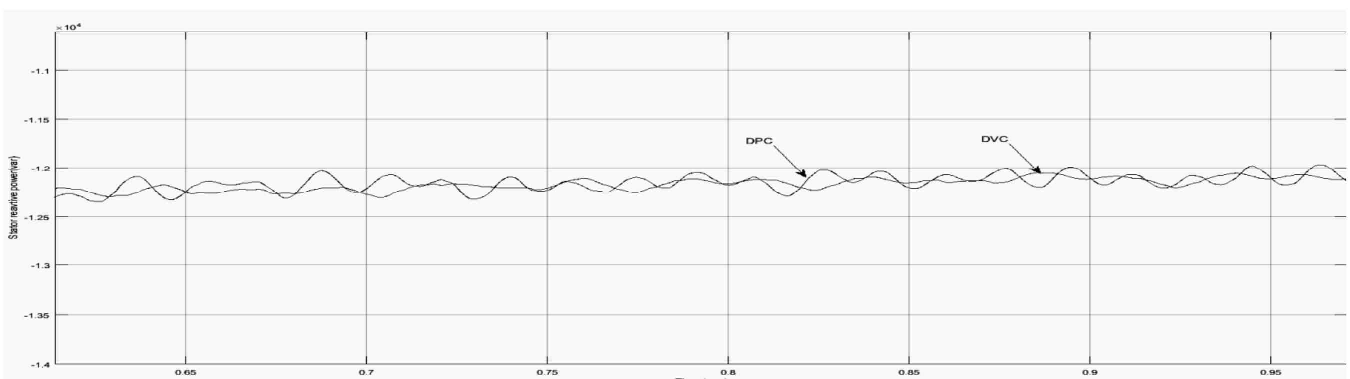

Figure 17: Stator Reactive power for DPC and DVC

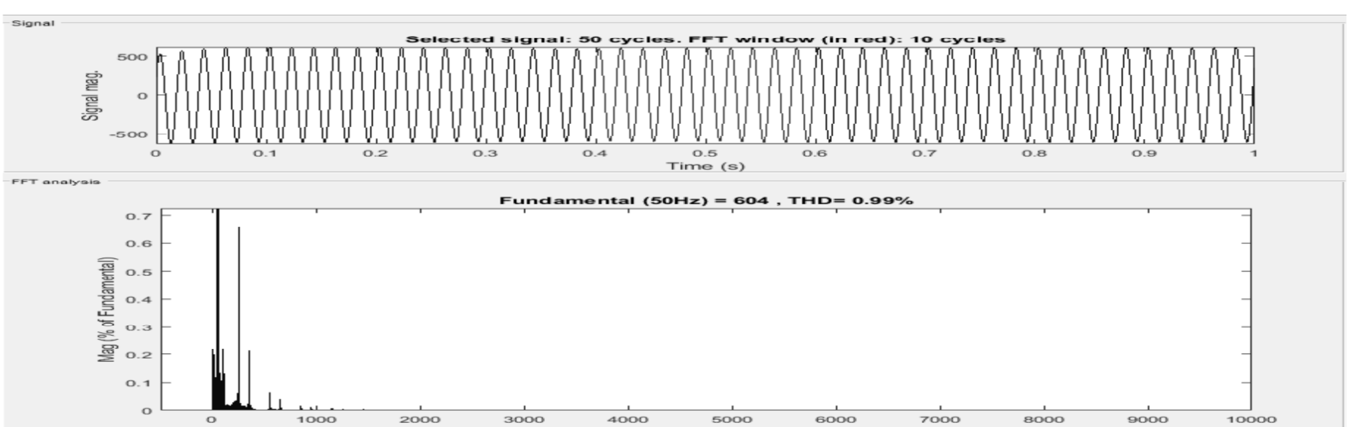

Figure 18: THD analysis for grid voltage (DPC) amounting to 0.99%

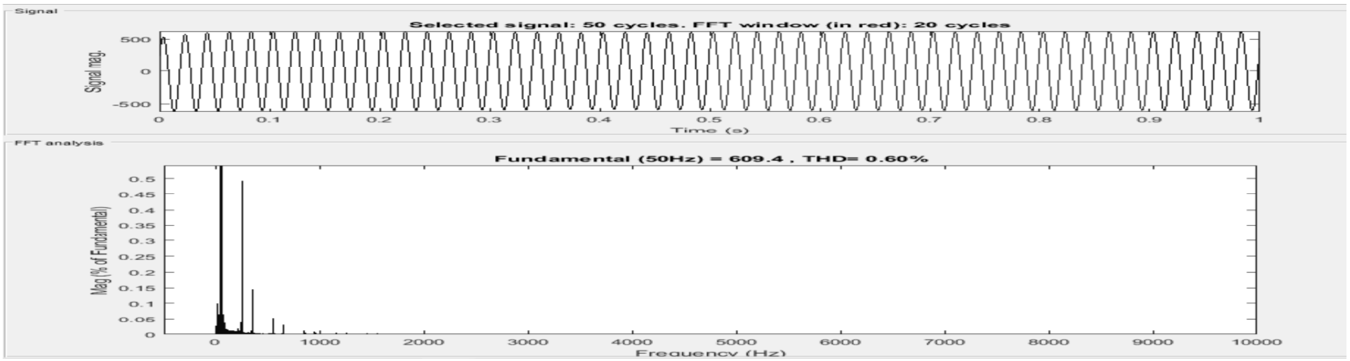

Figure 19: THD analysis for grid voltage (DVC) amounting to 0.6%

VII. CONCLUSIONS

A relative study of DPC and modified DVC is done at the RSC side. Performance of DFIG is analyzed using MATLAB simulation. THD levels are estimated using FFT which are according to IEEE standard. Comparative analysis shows that the DVC method is found to have less oscillation than that of DPC, and the settling time is less for DPC compared to DVC. The control technique used for DPC considers reference power values unlike DVC. Hence measures can be taken to increase the efficiency of DPC for efficient results with simplicity. The hardware implementation has been done by implementing open loop control. Pulses have been generated for control algorithm by using TMSC2000™ microcontroller. Three phase inverter output voltage has been achieved with 120 degree phase shift. Table 1 shows the simulation results for both the control methods.

Parameters	*DPC*		*DVC*	
	Sub synchronous Mode	*Super synchronous Mode*	*Sub synchronous Mode*	*Super synchronous Mode*
Rotor speed (rad/sec)	155.2	180.5	150	180
Stator active power (Watts)	Ps = -1010	Ps = -1010	Ps = -1000	Ps = -1000
Rotor active power (Watts)	Pr = 15	Pr = -613.5	Pr = 14	Pr = -612
Rotor reactive power (Watts)	Qr = 20	Qr = -12.5	Qr = 21	Qr = -12.5
DC link voltage (Volts)	Vdc = 440	Vdc = 440	Vdc = 440	Vdc = 440

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