Pumped Storage Power Plant Control System Modeling by Applying VSI and Vector control principle

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Abstract— This paper includes modeling and simulation of 180 MW units of pumped storage power plant with Variable speed machines. In this method, voltage source inverters are used instead of traditional cyclo-converters. This paper aims to control the voltage source inverters and maintain DC voltage at a constant value. AC/ DC/ AC converter is used in system configuration structure in order to control and change voltage and frequency. AC / DC converter is a three-phase rectifier bridge as well as DC / AC converter is a single phase inverter which includes 12 IGBT (insulated gate bipolar transistor) and output includes constant voltage designed from inverters output. Firstly, the control structure of the machine and the transformer sections will be described and the block diagram of each part is shown, then the equations for each part descried and the overall control structure of plant will be achieved. The simulation of this methods by applying Matlab software have been presented.

Index Terms-- VSI, Pumped storage power plant, Vector control, Reactive power control, Rotor side control, Grid side control, DFIG.

I. INTRODUCTION

The need for renewable energy sources is necessary due to increased demand, restricted traditional fuel sources, extended power network, stability and protection, therefore, the role of pumped storage power plants is necessary to achieve this goal. The issue of using variable speed machine technology in pumped storage power plants instead of fixed speed units with static frequency converter. The benefits of these plants include: efficiency increase in generation and demand mode especially in partial load, stability improve and fast responses in critical situations, most important of them is the possibility of changing absorbed power from network that exist at the pumping state and in the allowed range (30% of nominal power) which controls network frequency with high-performance.

Using inverter in variable speed power plant has several advantages, the most important of them include no need for reactive power compensator on the network side and no need for set up stator noted that enhances the efficiency of power plants [1, 2]. In [3] discusses the operation of a multiphase system, which is aimed at both variable-speed drive and generating applications, using back-to-back converter structure with dual three-phase machine-side converters. In this studied topology, an asymmetrical six-phase induction machine is controlled using two three-phase two-level voltage source converters connected in series to form a cascaded dc link is presented. In [4] the dynamic performances of variable speed and fixed speed units are compared in the case of 320MW pumped storage power plant. The case study of the pumped storage power plant with standard synchronous machine with PSS is presented. In [5] the control strategies for variable speed units of pumped storage by using the simplified model of the converter has been presented. In [6] the modeling and simulation study of a variable speed pump-storage power plant composed of a reversible turbine, a doubly fed induction machine (DFIM), and a multistage-multilevel frequency converter is presented. The DFIM rotor circuit is fed by a 5-level NPC VSI. The inverter DC-link capacitor voltages are kept in balance by means of four multistage PWM rectifiers. In this paper the voltage and frequency controllers are designed for easy implementation in a digital system such as DSP; the satisfactory performance of control scheme under dynamic conditions is shown in Matlab Simulink Using power system dynamic simulation. The basis plan is conducted through controlling voltage source three-level inverters based on state space control method; the aim is to control voltage source three-level converter and hold DC voltage at a constant value [7]. In this paper, the classic method is used in order to get overall transfer function of system and the location of poles and state space method is used in order to control reactive power and DC voltage. In fact, we try to stabilize the unstable parts of system for overall stability of system (unstable poles of system function).

Therefore, in this article two aims are considered for VSI systems.

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- DC voltage holding at a certain value
- Reactive power control in a fixed amount

In this method, power factor correctors are used wherever more accuracy is needed for power factor correction and high-speed dynamic response [8]. Accordingly, the system electrical structure and system overall configuration will be described in Part II, equations of state space systems will be written and then needed transfer functions will be made.

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II. OVERALL STRUCTURE OF SYSTEM

At first, the model is considered as two sections of transformer and machine and structure of each section will be explained and then, electrical part of system will be described. The electrical system schematic will be shown in Figure1.DFIG stator is usually tied with grid having fixed voltage and frequency and produces a constantly rotating filed flux. Rotor circuit is connected to grid through back to back converter thus control is performed at the rotor side by injecting a voltage or current of magnitude and frequency.

The converter at rotor side controls the speed of the DFIM and the real power flow to the grid whereas grid side converter controls the power factor and keeps the voltage of the DC link capacitor, connected between the both capacitor, constant. The Park method is intended for this purpose through 3-phase frame to d-q axis and d axis is related to active power and DC voltage and q axis is related reactive power. Suffixes q and d indicate the quantities in stationary q-d reference frame. Once reference frame is chosen and aligned with d axis then the rotor current which is controlling variable is transformed into dq components, [9] and [10].

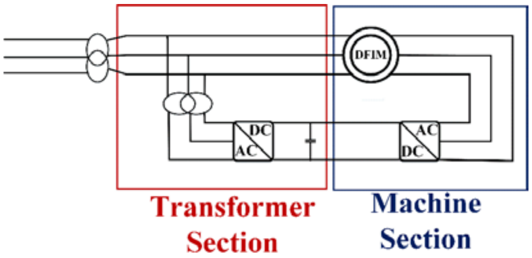

Fig 1. Variable speed power plant electric model

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III. VECTOR CONTROL PRINCIPLES

Three phase quantities of induction machine such as voltage, current and fluxes can be represented by space vectors. Vector control principles is the idea to control these quantities by controlling the magnitude and phase angel of their space vectors. Torque is produced due to interaction of stator and rotor fluxes and by controlling torque, real power flow of machine can be controlled.

3.1 Rotor Side Converter

The real and reactive power of the stator is controlled through d and q axis rotor currents respectively. Stator voltage vector is aligned to the d axis of rotating reference frame this makes stator voltage equal to equation (1):

$$\vec{v_s} = v_{sd} \tag{1}$$

$$v_{sq} = 0 \tag{2}$$

$$\vec{\lambda_s} = \int (\vec{v_s} + R_s \vec{i_s})\, dt \tag{3}$$

Stator flux lags the stator voltage almost at $\frac{\pi}{2}$, after aligning with d axis of rotating frame and neglecting resistance drop in flux equation (3), result in :

$$\vec{\lambda_s} = \lambda_{sq}\,(const) \xrightarrow[then]{} \frac{d}{dt}\lambda_{sq} \approx 0 \tag{4}$$

$$\lambda_{sd} = 0 \xrightarrow[then]{} \frac{d}{dt}\lambda_s = 0 \tag{5}$$

3.2 Rotor Speed

Rotor speed reference will be generated by optimum efficiency speed module base on power reference. This reference will be used to compute electromagnetic torque reference which will be used further to generated current reference for d axis rotor $i_{rd,ref}$. The speed controller to produce torque reference will be shown in figure 2.

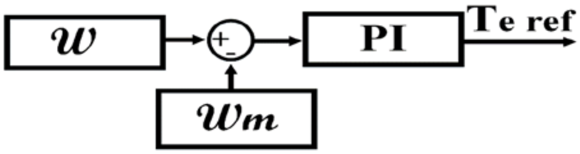

Fig 2. Speed controller to produce torque reference

The torque for control the speed is illustrated by equation (6). Stator flux is fixed as stator tied to the grid, then the i_{sd} in equation (6) can be replace with stator flux current relation for chosen the reference frame to find torque relation is term of rotor current as equation (7):

$$T_e = -\frac{3}{2} p_p\,(i_{sd}\lambda_{sq}) \tag{6}$$

$$T_e = -\frac{3}{2} p_p \left(\frac{-L_m \lambda_{sd}}{L_s}\right) i_{rd} \tag{7}$$

Then the equation (8) is reference current for rotor d axis current controller which is used for generated the voltage for VSI switching production.

$$i_{rd} = \frac{2}{3}\,\frac{1}{p_p}\,\left(\frac{T_e L_s}{L_m \lambda_{sq}}\right) \tag{8}$$

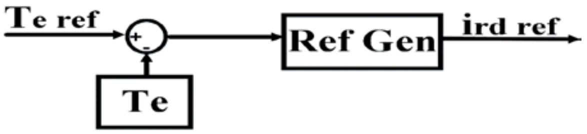

Fig 3. D-axis rotor current reference generation for RSC.

3.3 Rotor Voltage

The reference rotor current $i_{rd,ref}$ will be compared with measured d axis current and inner PI loop will generated the d axis rotor voltage which is applied to the rotor side converter. So the elimination cross coupling terms in rotor voltage can be described in equations (9) and (10):

$$V_{rd} = R_r\, i_{rd} + \frac{d}{dt}\lambda_{rd} \qquad (9)$$

$$V_{rq} = R_r\, i_{rq} + \frac{d}{dt}\lambda_{rq} \qquad (10)$$

The control variable is rotor current so equation needs to be represented in terms of rotor current. Stator current for chosen reference frame are:

$$i_{sd} = \frac{-L_m\, i_{rd}}{L_s} \qquad (11)$$

$$i_{sq} = \frac{\lambda_{sq} - L_m\, i_{rd}}{L_s} \qquad (12)$$

$$\lambda_{rd} = L_r i_{rd} + L_m \left(\frac{-L_m\, i_{rd}}{L_s}\right) \qquad (13)$$

$$\lambda_{rq} = L_r i_{rq} + L_m \left(\frac{\lambda_{sq} - L_m\, i_{rq}}{L_s}\right) \qquad (14)$$

Putting the equation (11), (12), (13), (14) in rotor voltage equations (9) and (10) the result is:

$$v_{rd} = R_r\, i_{rd} + \left(\frac{L_r L_s - L_m^2}{L_s}\right)\frac{d}{dt}\, i_{rd} \qquad (15)$$

$$v_{rq} = R_r\, i_{rq} + \left(\frac{L_r L_s - L_m^2}{L_s}\right)\frac{d}{dt}\, i_{rq} \qquad (16)$$

Figure 4, shows the complete d axis cascaded loop with compensation for speed control.

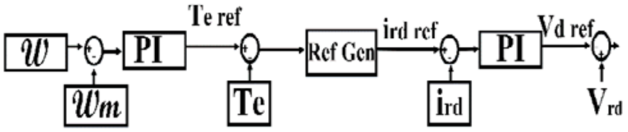

Fig 4. Complete d-axis cascaded loop with compensation.

3.4 Reactive Power Control of RSC

Reactive power of stator in term of dq components can be written as equation (17):

$$q_s = \frac{3}{2}\left(v_{sd}\, i_{sq} - v_{sq}\, i_{sd}\right) \qquad (17)$$

As explained earlier that power at the stator is controlled through rotor side converter and RSC current controller needs reference rotor currents to produce control voltage. Therefore, to generate reference rotor current for reactive power the equation (17) can be rewritten with equation (18):

$$i_{sq} = \frac{\lambda_{sq} - L_m\, i_{rq}}{L_s} \qquad 18)$$

$$q_s = \frac{3}{2}\, v_{sd}\left(\frac{\lambda_{sq} - L_m i_{rq}}{L_s}\right) \qquad (19)$$

Rearranging equation (19):

$$i_{rq} = \left(\frac{\lambda_{sq}}{L_m} - \frac{2}{3}\,\frac{q_s L_s}{v_{sd} L_m}\right) \qquad (20)$$

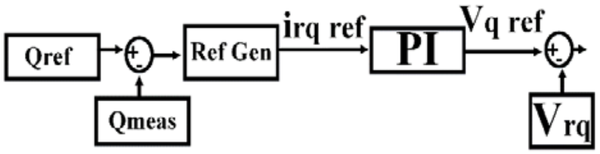

Fig 5. Complete q-axis loop with compensation

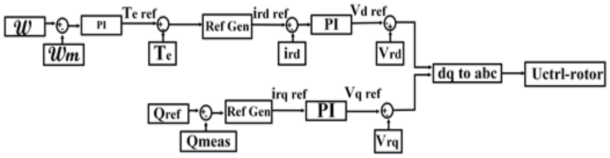

Fig 6. The block diagram of the Rotor control

3.5 Grid Sid Converter

Grid side converter maintains the voltage across DC link capacitor and can also exchange reactive power to and from grid and can work as both rectifier and inverter. DC link voltage depends on power flow between RSC and GSC. When the power flows from RSC toward DC link capacitor the grid should supply excess power to the grid otherwise this excess power will raise the voltage across capacitor. Similarly when the power flows from DC link capacitor to rotor the gird must supply the power required otherwise DC link voltage will drop.

3.6 DC Link Control Loop

Power from RSC for d-axis aligned with stator voltage vector can be written as equation (21):

$$P_r = \frac{3}{2}\left(v_{rd} i_{rd} + v_{rq} i_{rq}\right) \qquad (21)$$

And the power for grid side converter is:

$$P_g = \frac{3}{2}\left(v_{gd}\, i_{gd} + v_{gq}\, i_{gq}\right) \qquad (22)$$

The d axis is rotating at synchronous speed of grid frequency, and is aligned with the grid voltage d axis for grid side converter control so equation (22) becomes:

$$P_g = \frac{3}{2}\left(v_{gd}\, i_{gd}\right) \qquad (23)$$

Then dynamic power equation in terms of voltage across DC link capacitor can be written as:

$$P_g - P_r = \frac{1}{2}\, C_{DC} \frac{d}{dt} V_{DC}^2 \qquad (24)$$

To write the control equation for DC link controller in terms of grid current i_{gd} rotor power P_r term can be considered as disturbance then equation (24) reduces to:

$$P_g = \frac{3}{2}\, v_{gd}\, i_{gd} = \frac{1}{2}\, C_{DC} \frac{d}{dt}\, v_{DC}^2 \qquad (25)$$

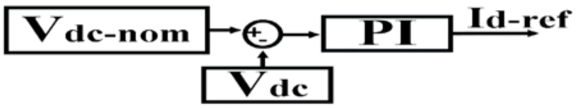

Fig 7. Reference generation for d-axis current loop of GSC.

3.7 Grid Voltage

Grid voltage equations have already been written for dq grid model. After writing the equations of the voltage in the dq stationary, for the selected grid voltage reference frame as:

$$v_{gd} = R_f\, i_{gd} + L_f \frac{d}{dt}\, i_{gd} + v_{fd} - \omega_g\, L_f\, i_{gd} \qquad (26)$$

$$v_{gq} = R_f\, i_{gq} + L_f \frac{d}{dt}\, i_{gq} + v_{fq} + \omega_g\, L_f\, i_{gd} \qquad (27)$$

Where ω_g is grid frequency.

3.8 Reactive Power Control of GSC

Reactive power exchange at grid side in terms of dq components can be written as:

$$q_g = \frac{3}{2}\left(v_{gd}\, i_{gq} - v_{gq}\, i_{gd}\right) \qquad (28)$$

Grid voltage is aligned to the d-axis of reference frame rotating at grid frequency.

$$\overrightarrow{v_g} = v_{gd} \qquad (29)$$

$$v_{gq} = 0 \qquad (30)$$

Thus reactive power equation (28) reduces to equation (31):

$$q_g = \frac{-3}{2}\, v_{gd}\, i_{gq} \qquad (31)$$

This equation (31) can be rearranged to produce reference current signal $i_{gq,ref}$ for inner loop of grid converter controller as:

$$i_{gq} = -\,\frac{2}{3}\,\frac{q_g}{v_{gd}} \qquad (32)$$

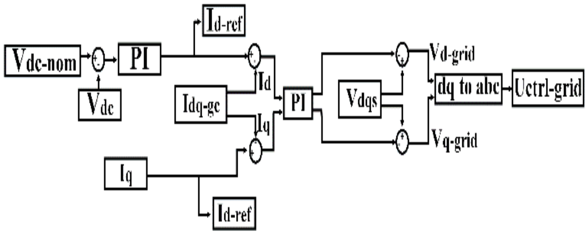

Fig 8. The block diagram of the grid control

IV. SIMULATION RESULT

In This simulation, the switching converter through Svpvm method is designed [18]. The different control structures existed in references [19], [20]. The equation of the machine section has been considered in the simulation results. The simulation is done through considering a180 MW variable speed pumped storage power plant unit. Circuit required parameters are presented in Table 1. Parameters used in simulation are per united based on nominal values of transformer. The nominal values include:

Simulated noise with a mean of -0.8 and variance of 5% is obtained using random function. The simulation results are expressed in below figure. The results of the simulation have been investigated in Matlab software. In this case all parameters are based on the 180 MW Azad power plant in Iran .In figure 9 active power achieving resulted from simulation in Matlab software .In Figure 10 and 11 show the stator current and stator voltage from grid side and figure 12 show rotor current from rotor side converter. In figure13show the torque resulted from DFIM in simulation in Matlab and figure 14 show The DC link voltage from simulation in constant value. In figure 15 show the switching from Svpwm method in VSI by dynamic voltage. Figure 16 show the voltage from conversion in dq reference from DFIM

Table1 Case study parameters

Mutual Reactance (Pu)	0.5
Rotor Reactance (Pu)	0.101
Rotor Resistance (Pu)	0.01453
Stator Reactance (Pu)	0.1
Rotor Resistance (Pu)	0.01393
Rotor Voltage (kV)	3
Stator Voltage (kV)	18
Active Power (MW)	180
Apparent power (MVA)	306
Rotor inertia (tm^2)	1200
Coupling	Yy0
Apparent power (MVA)	26.7

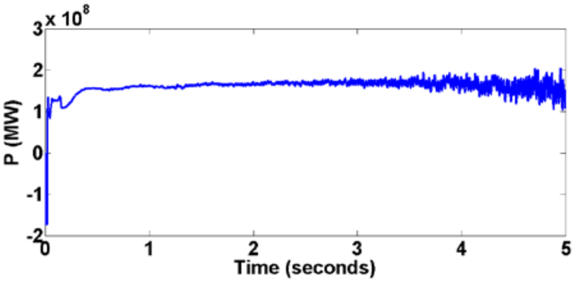

Fig 9. The active power (180MW) resulted from simulation

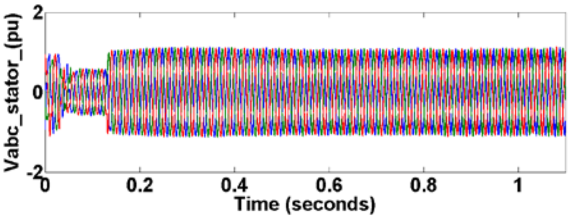

Fig 10. The stator voltage from grid side converter

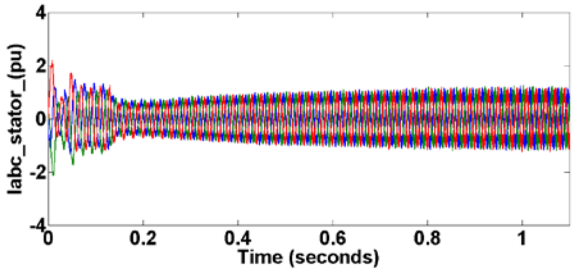

Fig 11. The stator current from grid side converter

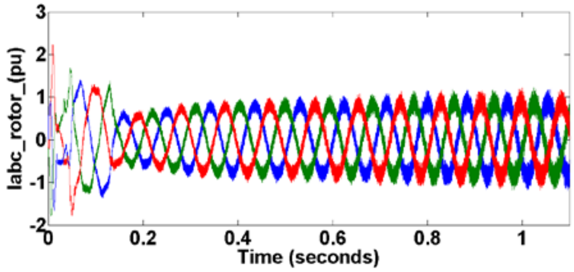

Fig 12. The rotor current from rotor side converter

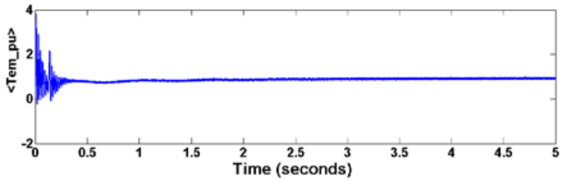

Fig 13. The torque resulted from DFIM in simulation

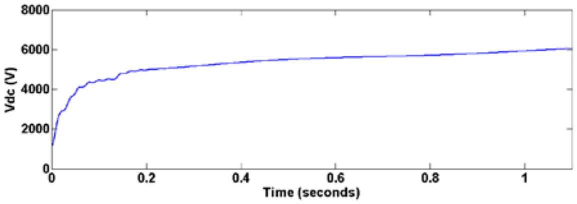

Fig 14. The DC link voltage from simulation in constant value

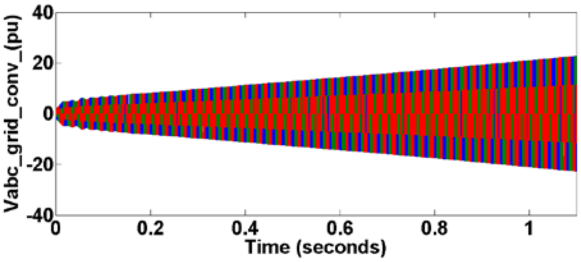

Fig 15. The Grid voltage from Svpwm switching

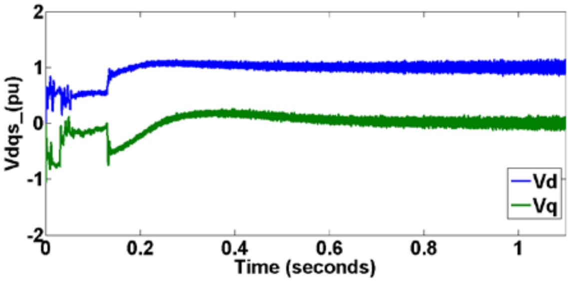

Fig 16. The conversion voltage in dq reference

V. CONCLUSION

In this article, one of the 180 MW pumped storage power plant units was simulated with using MATLAB software. This simulation is done in both classical and state-space control. In line with simulation implementation, all parts of machine and transformer are included and calculated. Then using compensation, poles for stability system is calculated. Modeling and simulation results show better network control capabilities and high dynamics and have more maneuver and flexibility capabilities compared to constant speed power plants. Also, Comparison of reactive power in two method show improved response time to network reactive power need in monitoring in state space control, and little difference current control obtained from classic control and state space.

The amount of input noise to system is reduced. The difference between input and output is stored or released as rotor speed in variable speed machines due to flywheel effect.

In addition, no need to compensate reactive power on network side compared to old structure is other advantage of this method. Also, using VSI is increased due to high-speed responsiveness through modifying some of limitations (eg switching); the initial costs and operation of variable speed double- feed power plant units is are, but the power plant speed, stability, whole and retail efficiency are improved.

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