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Synchronization and Coordinated Fuzzy Current Control Scheme of PMSG Based WECS in the Presence Of Severe Grid Fault

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Abstract* —When ever extreme grid collapse occurs, the wind farm should remain on-grid and the desired reactive current must be injected in to the grid, which is generally required by the grid codes. Static synchronous compensator (STATCOM) is used in order to inject certain reactive current, it is normally used in wind farms in the present scenario. Generally, some of the vector control methods like phase locked loop (PLL)-oriented are used to control the wind farm and STATCOM to supply reactive currents. Even due to severe grid fault there is a chance of occurring loss of synchronization (LOS) due to imbalance of real power between supply of power and utilization. The dynamic mechanism of synchronization and wind farm stability criteria and proposes coordinated fuzzy current control scheme for the WECS and STATCOM under grid fault. PI controller is replaced with Fuzzy logic controller in this proposed method. The proposed control scheme is verified and carried out simulations in MATLAB/SIMULINK.

***Index Terms* — permanent magnet synchronous generator (PMSG), wind energy conversion system (WECS) , coordinated fuzzy current control.**

I. INTRODUCTION

Now a days a enormous wind energy is incorporated in to the system. This affect shows on the system stability, which is becoming the important criteria in the present scenario. The wind characteristics should be standardized and grid operators recommend grid codes to tackle such situation .we take so many grid codes among those one of the most popular grid code is LVRT. This code demands WECS remains associated and the required wattless current should be injected to assist the grid through out the abnormal condition. The requirements of this grid code are as shown in fig1. When severe grid fault occurs ,the WECS should provide reactive currents during that period. Below 50% of voltage sag the reactive currents should be supplied twice the percentage. If the voltage sag is above the 50% then the reactive currents be supplied 100%.

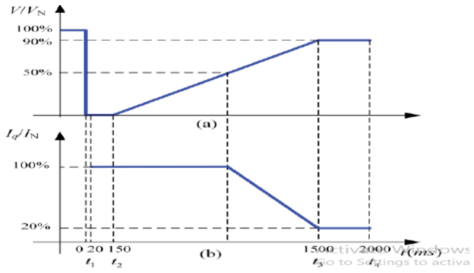

Fig .1. The requirements of LVRT grid code.

In the studies which were made previously, the LVRT schemes were broadly discussed. From these studies, the observation is to balance power converter voltage across dc-link during fault period is the major difficulty of WECS control. It was verified that, because of the flexibility of control of its full scale converter the PMSG based wind farm could achieve the grid code demands.

Fuzzy management has transpired as the foremost active and fruitful analysis area, due to lack of quantitative input and output data for conventional methods. If this management depends on fuzzy logic, then the system is far nearer to logical thinking of a human being and communication of linguistic variables than ancient language.

This paper analyses the effective LOS technique for wind power plant provided with STATCOM and WECS .This paper put forward a coordinated fuzzy current control scheme for WECS to maintain synchronism under fault conditions. The grid and generator side converters control objectives were swapped to resolve it's problem between synchronization and voltage control of dc-link. The proposed current control schemes are verified using MATLAB/SIMULINK.

II. SYSTEM CONFIGURATION AND MODELING

The wind power plant having PMSG layout was given in Fig .2.

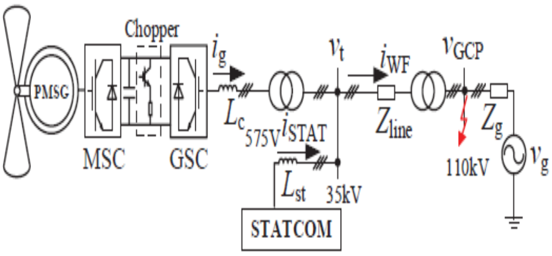

Fig 2. Layout of the wind power plant having PMSG

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The wind energy facility has been represented by an lumped WECS .There are two stage transformers which are combinely connected to the grid along with wind farm. The power grid can be shown by using thevenins equivalent circuit, where v_g represents thevenins voltage and Z_g represents equivalent internal impedance. v_t represents point of common coupling (PCC) voltage and V_{GCP} represents grid connection point (GCP) voltage. i_{WF} represents the wind farm output current and i_{STAT} represents STATCOM current. Z_{line} is the transmission line impedance and L_c, L_{st} are the Windfarm and the STATCOM grid tie inductances.

A. *Design of the Wind farm having PMSG*

The wind energy converter power equation is given by[24] :

$$P_m = \frac{1}{2}\pi R^2 \rho v^3 C_p$$

R indicates radius of turbine, *p* indicates density of air and v indicates velocity of wind flow; *C_p* is the coefficient of the turbine which is a non linear function of angle of pitch β ,the speed of wind, the rotational speed of the prime mover.

$$J_h \dot{\omega}_h = T_{wt} - K\theta$$

$$J_g \dot{\omega}_m = K\theta - T_e$$

$$\dot{\theta} = \omega_h - \omega_m$$

The WECS drive train is having so much flexibility and two mass spring model was used to exemplify its dynamics. The WECS mechanical subsystem can be given as [24] :

where w_h,w_m are the wind turbine and generator rotational speed . J_h ,J_m are the inertias of prime- mover and alternator. θ represents rotational shaft electrical angle; K represents stiffness of the shaft; T_{wt}, T_c are the mechanical torque and generator torques.

The PMSG model can be explained as [25] :

$$v_{sd} = R_s i_{sd} + L_d \dot{i}_{sd} - L_q p_n \omega_m i_{sq}$$

$$v_{sq} = R_s i_{sq} + L_d \dot{i}_{sq} + L_d p_n \omega_m i_{sd} + \psi_r p_n \omega_m$$

$$T_e = \frac{3}{2} p_n \left[(L_d - L_q) i_{sd} i_{sq} + \psi_r i_{sq} \right]$$

where v_{td}, v_{tq} are the voltages of the stator along dq axis; L_d, L_q are the stator inductances of the d axis and q axis and R_s represents stator winding resistance.

The grid side converter model is designed here as an instance.

$$L_c \dot{i}_{gd} = v_{cd} - v_{td} + \omega_g L_c i_{gq}$$

$$L_c \dot{i}_{gq} = v_{cq} - v_{tq} - \omega_g L_c i_{gd}$$

$$C_{dc} \dot{V}_{dc} = -\frac{3}{2V_{dc}}(v_{cd} i_{gd} + v_{cq} i_{gq}) + i_{dc\_rc}$$

where v_{td}, v_{tq} are the voltages of the grid along dq axis and i_{gd}, i_{gq} are the currents along dq axis; v_{cd},v_{cq} are the output voltage of the converter along dq axis ; $i_{dc}\_r_c$ represents dc injected current in to the rectifier which is at generator-side ; V_{dc}, represents voltage of dc-link and C_{dc} represents capacitance of dc-link.

The real power output of a converter which is at the grid side could be done using the equation given below [26] :

$$P_g = \frac{3}{2}(v_{td} i_{gd} + v_{tq} i_{gq})$$

The STATCOM model is not explained here as it is same as above converter model [27].

B. *Design of the PLL*

The classic model of PLL is as depicted in below Fig.3 [19]

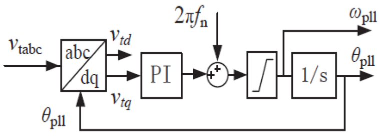


Fig 3. Typical PLL diagram

The association between the grid voltage along q axis and the frequency which was observed is given by:

$$\frac{d\omega_{pll}}{dt} = K_p \frac{dv_{tq}}{dt} + K_i v_{tq}$$

where θ_{pll} and ω_{pll} are the PLL outputs ; K_p and K are the PI regulator proportional and integral coefficients.

III. PMSG BASED WINDFARM ANALYSIS OF SYNCHRONISM

When ever the grid voltage drop occurs during initial few cycles ,the response of a converter will results in the formation of voltage transients. Especially for WECS and STATCOM, over voltage and over current protection will be provided by the additional protective devices like dc choppers. When the severe grid fault the wind farm require some reactive current support by some external means and must be controlled and to provide some sort of support to the grid during fault period.

Consider the situation that grid failure occurs at the GCP . The V_{GCP} can be mainly depends on transmission line impedance and its value could be determined by the short circuit. When ever severe fault occurs ,the LOS (loss of synchronization) is usually the most common issue and the impedance during short circuit is very low. The grid under fault can be depicted as an ideal voltage source v_f and its equivalent impedance was neglected. The WECS is responsible to supply pure reactive current, when severe grid fault occurs, hence it was represented as a current source. The typical model of the WF during severe grid fault is portrayed in the Fig.4, the equivalent line impedance is given by

$$Z_l = Z_{line} + Z_{T2} = R_g + jL_g$$

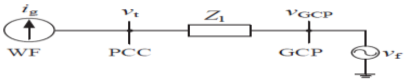


Fig .4. Analogous Wind Farm model under fault condition

By referring to the above equivalent model , some simplified expressions can be derived in the reference frame of dq:

$$\begin{bmatrix} v_{td} \\ v_{tq} \end{bmatrix} = \boldsymbol{T} \cdot \begin{bmatrix} v_f \\ 0 \end{bmatrix} + \omega_{pll} L_g \begin{bmatrix} -i_{gq} \\ i_{gd} \end{bmatrix} + R_g \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + L_g \frac{d}{dt} \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix}$$

where T is the transformation matrix,

$$\boldsymbol{T} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix}$$

The equivalent thevenin impedance L_g usually remains constant, but it may change when number of lines and WECS's which are associated with the grid changes. Hence L_g can be treated as a variable coefficient.The current dynamic in the synchronization issues can be ignored, that means $i_{gd}=i_{gd}^*$, $i_{gq}=i_{gq}^*$. i_{gd}^*,i_{gq}^* are generally found by the grid code which are WECS current commands.

Substituting above two equations , the below expression can be determined from the equation given by $\frac{d\delta}{dt} = \omega_{\mathrm{pll}} - \omega_{\mathrm{g}}$ as depicted in fig .5.

$$\left(1-K_p L_g i_{gd}\right)\frac{d}{dt}\omega_{pll} = -K_p v_f \cos\delta\left(\omega_{pll}-\omega_g\right)+K_i v_{tq}$$

$$-\frac{3}{2K_i}i_{gq}^*\left(1-K_p L_g i_{gd}\right)\frac{d}{dt}\omega_{pll} = \frac{3}{2}i_{gd}^* v_{td} - \frac{3}{2}\left(i_{gq}v_{tq}+i_{gd}v_{td}\right) + \frac{3}{2K_i}i_{gq}^* K_p v_f \cos\delta\left(\omega_{pll}-\omega_g\right)$$

In the rotating reference frame of the vector oriented grid voltage, the real power reference of the wind farm $P_o^* = 1.5 \times i_{gd}^* v_{td}$. The swing function is given by

$$J_{eq}\frac{d\omega_{\mathrm{pll}}}{dt} = P_{\mathrm{o}}^* - P_{\mathrm{g}} - D_{eq}\left(\omega_{\mathrm{pll}}-\omega_{\mathrm{g}}\right)$$

where,

$$J_{eq} = -\frac{3}{2K_i}i_{gq}^*\left(1-K_p L_g i_{gd}\right), D_{eq} = -\frac{3K_p}{2K_i}i_{gq}^* v_f \cos\delta$$

are the damp factor of WECS and equivalent virtual inertia. Consider that during fault period LOS problem will happens usually in most of the cases. As v_f is very low value , D_{eq} can be neglected.

In order to maintain the WECS synchronization dynamic stable it is necessary to keep J_{eq} remains positive .The K_p, K_i of the PLL which are very low values are useful in order to maintain stability of the WECS. This proves that the PLL which is slow is helpful to maintain synchronization stability under severe grid fault circumstances. The smaller L_g also plays role in maintaining stability. The above equation also indicates that LOS issue is because of the imbalance in the active power supply in the power system.

From the above analyses, some conclusions were drawn:

If $P_o^*>P_g$, the WECS frequency keeps on increasing.

If $P_o^*=P_g$, the WECS frequency remains stable.

If $P_o^*<P_g$, the WECS frequency keeps on decreasing.

The complete model of Fig.2 simulations are executed in Eventually, when ever the severe voltage drop occurs, the WECS has to provide reactive power which was generally required by the grid codes and P_o^* must be equal to zero. The components of real and quadrature current both will passes through the power system and both are equally responsible to produce active power loss which is in the form of heat.

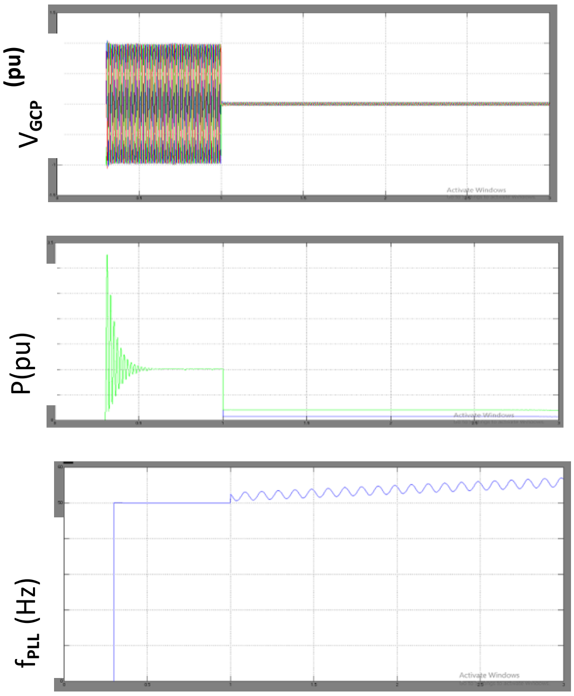
Eventually, when ever the extreme voltage drop occurs, the WECS has to provide reactive power which was generally required by the grid codes and Po* must be equal to zero. The components of real and watt less current both will passes through the power system network and both are equally responsible to produce active power loss which is in the form of heat. The system remains stable only when the source of supply and utilization both are same. The current source ig and voltage vf, is responsible to provide transmission line real power loss. The grid was unable to supply active power loss, when vf is very low value. Hence the WECS has to supply active power loss , otherwise it would result mismatch between Pg and Po*, which is its reference value. This mismatch can lead to WECS to lose its synchronization. To attain synchronization stability, the real power reference Po* has to be changed and made equal with Pg during the fault. Especially for the STATCOM, which is a reactive power compensator and not having the capability to control active power in the line hence chances of occurring of LOS can not be refrained.

In order to improve synchronization stability, more active power is necessary to be injected but this will lead to reduction of reactive power capability of WECS. This is because due to power converters current rating limitation. The togetherness of the WECS and STATCOM very much needed, because WECS is responsible to maintain synchronization stability in turn it helps STATCOM from LOS issue. STATCOM is responsible to compensate reactive current.

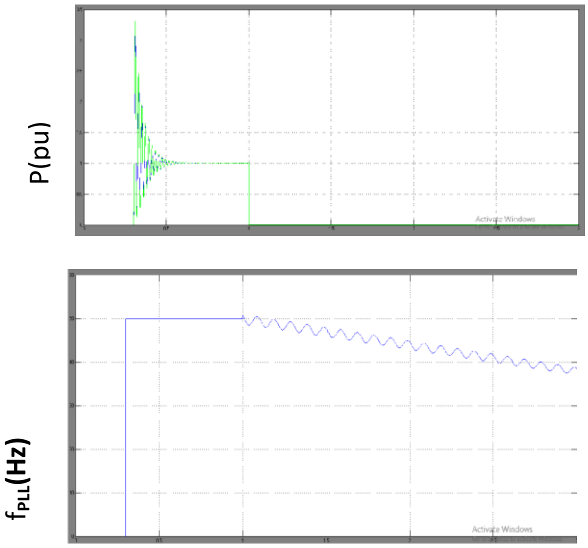
A. *Fuzzy logic controller:*

The fuzzy logic has rapidly turned out to be a standout amongst the present best innovations for advanced control frameworks improvement, quickly become one of the today's most successful technologies for sophisticated control systems development. It is a mathematical tool for managing vulnerability. Fuzzy logic systems have quicker and smooth response when compared with conventional systems and have less control complexity. A Fuzzy set is described by a function that maps objects to their membership value in the set, in the domain of concern. Such function is referred to as a membership function. The selection of inputs and outputs in the form of membership function so as to design Fis. Fuzzy rule base has if-then statements, where fuzzy control rule depends on Fuzzy decision making. Fuzzy logic controller is used in the place of PI controller in order to get enhanced output.

The simulation results are verified using MATLAB/SIMULINK with the introduction of fuzzy logic controller in it. Exactly at t=1sec, the grid fault takes place and the voltage at the GCP falls to 0.02 pu. The WECS real power reference can alters and it's outcomes are depicted in Fig. 6. If P_o^* is not equal to its actual value P_g, then the PLL frequency doesn't get synchronize with frequency of the grid.



(a) Po'>Pg



(b) P_o'<P_g

Fig. 6. The WECS frequency response

IV. COORDINATINGCONTROL SCHEME FOR WINDFARM AND STATCOM

When ever the severe voltage dip occurs, the above analyses proves that there may be high risk of LOS in the WECS. Hence in between wind farm having PMSG and STATCOM, a coordinated current control design is necessary to maintain stability and to reach reactive current requirements set by the grid code operators. In many previous studies of WECS control schemes the grid-side converter maintains dc link voltage and provides reactive current control. The generator side converter is responsible to achieve wind farm maximum power point tracking (MPPT). Under severe fault condition, to balance voltage across dc-link the extra reactive current has to be supplied by the grid side converter. To reduce excess amount of power in the DC link, the active power has to be with drawn from the wind by the generator side converter. Otherwise it may trip due to protection due to over voltages. This type of scheme is very difficult to design under LOS issue. Because here two issues will be contradicted to each other, those issues are control of voltage across DC-link and control of synchronization stability.

To resolve this problem further studies are made by swapping both control schemes of the both converters. The converter present at the side of generator is responsible to manage voltage across dc-link. The converter present at the side of grid takes charge of LOS issue and wattless current generation. Hence this problem can be resolved by that the real power drawn out from the generator side converter can be reduced with the increase in the dc link voltage.

A. *Control diagram of grid-side converter*

The real power imbalance is the major reason for LOS issue and the PLL frequency detected was set aside accordingly. To maintain power balance and the stability, the true power reference is given by $P_o^* = P_g + k_{ep}\Delta\omega$

where k_{ep} is proportional coefficient. $\Delta\omega = \omega_{gn} - \omega_{pll}$

and w_{gm} is the grid frequency nominal value. The w_g is the dynamic grid frequency can be neglected in the below equation .

$$J_{eq}\frac{d\omega_{pll}}{dt} + (k_{ep} + D_{eq})\omega_{pll} - (k_{ep}\omega_{gn} + D_{eq}\omega_g) = 0$$

D_{eq} should be negative, and it is a low value and then it will be simple to choose k_{ep}. The larger value of k_{ep} represents more fast dynamic response.

$$\lim_{t\to\infty}\omega_{pll} = \frac{k_{ep}\omega_{gn} + D_{eq}\omega_g}{k_{ep} + D_{eq}} \approx \omega_g$$

In general case ,the grid-side converter is preferred for MPPT operation. For MPPT power control, the d-axis must be taken as reference and in order to achieve unit power factor output q-axis current must be set to zero.

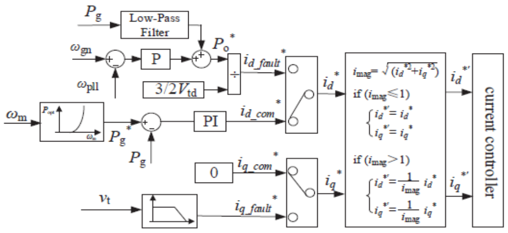


Fig. 7 Grid-side converter control design

B. *Control design of statcom*

When the voltage dip was very severe, then STATCOM will face the risk of LOS. If at the point of common coupling, the statcom connection is given then the reactive current provided by it can also have chance of occurring loss of real power in the line. But this loss can be compensated by the WECS, as this loss will create a power imbalance will make the PLL frequency cause a drift and which shows its affect on WECS active power reference.

As the voltage dip depth goes on increasing, correspondingly the active power produced by WECS is more and reactive current will be less. This shows that WECS lost its capability of providing reactive current hence it is very much needed to synchronize with STATCOM to provide reactive current in order to help WECS. V_{dcs} and V_{dcs}* are reference and true values of STATCOM dc link voltage.

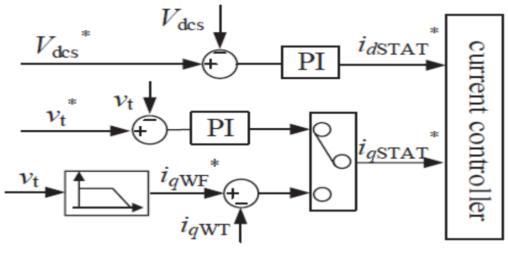


Fig. 8. STATCOM control design

C. *Generator-side converter control diagram*

The converter exists at the generator-side main purpose is to maintain power converter voltage across dc-link. It was generally found out by the difference between grid-side converter power output and generator-side converter active power. The converter exists at the grid-side is responsible to resolve LOS issue and the converter across generator-side is responsible to balance active power parellely voltage across dc-link .

Here no need of any extra control and communication equipment to design the scheme of coordinated current control. The PCC voltage is detected by the WECS and when ever its voltage is very low.

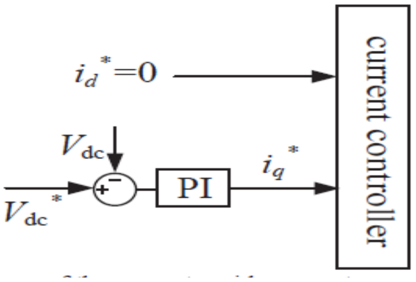


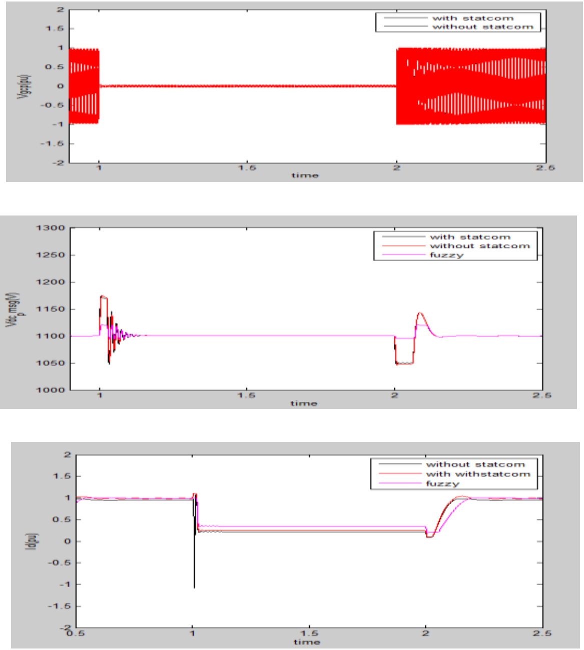
Fig. 9 Generator-side converter control design

V. SIMULATION RESULTS

The simulations of above analyses must be done in MATLAB to check variations of all terms and the above described control strategy effectiveness can be shown. Consider PMSG based WECS of 100MW and STATCOM is of 20MW. The short circuit fault which is symmetrical of three phase takes place at t=1sec.

A. *Proposed control strategy*

The short circuit fault of three phase symmetrical occurs at t=1sec and comes to zero at t=2sec.The GCP voltage falls down to 0.02pu. Due to the presence of drops in voltage present in the power system network, the terminal voltage increased to such a high value. The coordinated fuzzy current control scheme was designed and its effectiveness is verified and simulations were compared between statcom and without statcom and statcom using fuzzy controller using MATLAB/SIMULINK. Consider a fault happens at t=1sec and ends at t=2sec.



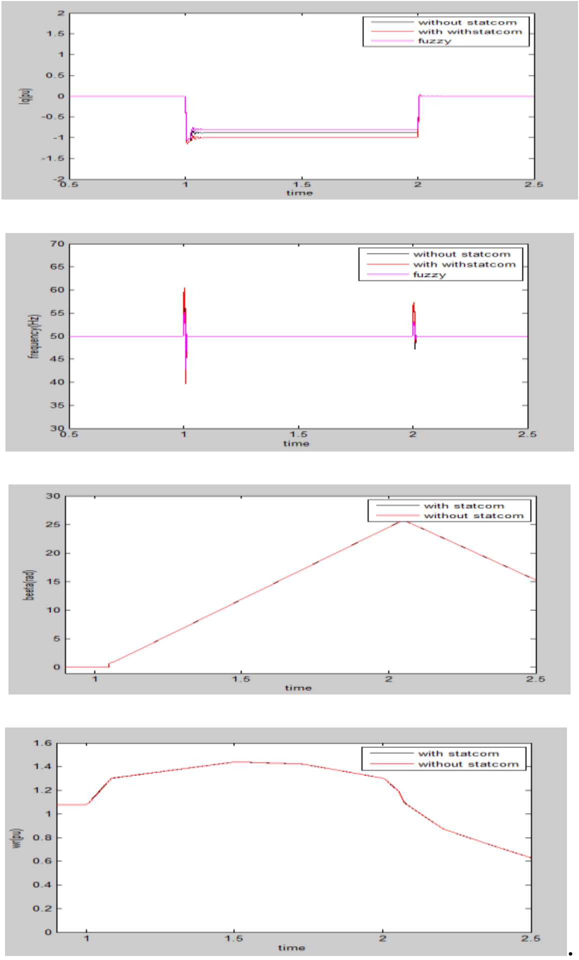


Fig 10.coordinated fuzzy control scheme response under fault condition

In all above cases considered, the synchronization stability can be maintained in between STATCOM and wind farm. The generator-side converter takes the responsibility to control dc-link voltage. The reactive current supply is under the control of grid-side converter with out the interaction of dc-link voltage control loop and synchronization control loop.

VI. CONCLUSION

This paper proposes a coordinated fuzzy current control scheme in order to achieve the synchronization stability and reactive current supply, during grid fault. The theoretical analyses and the simulation results were verified. Generally the wind farm and STATCOM during severe fault will suffer from LOS issue. This paper also proposes the perfect balance scheme for active power control. The active power balance mainly depends on the PLL frequency in order to attain WECS synchronization stability. The WECS will give up reactive current supply ability in this scheme. Hence assistance of STATCOM is very much needed for WECS to provide reactive current support. The synchronization issue will be more complex under grid fault, by considering more control loops associated with PLL's . Further studies are anticipated in this issue.

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