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Fuzzy Sliding Mode based PI Controlled UPFC for Optimized WECS Dynamics during Fault Ride Through

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ABSTRACT

With the enormous global growth in electrical power demand and the associated decrease in conventional power resources, electricity generation from renewable energy sources have been furiously sought worldwide, as they represent infinite and clean natural resources. Wind energy is one of the most efficient renewable energy sources. However, due to the fluctuating behaviour of wind energy and the need of electronic devices to link wind turbine generator with existing electricity grids, problems such as frequency oscillations, voltage instability and harmonic distortion may arise. Flexible alternative current transmission system (FACTS) devices, such as unified power flow controller (UPFC), can provide technical solutions to improve the overall performance of wind energy conversion systems (WECS). This paper presents a comparative study of transient stability and reactive power compensation issues in an autonomous wind energy conversion system (WECS) using robust fuzzy-sliding mode based unified power flow controller (UPFC). It is noted from the simulation results that the performance of UPFC is superior to static VAR compensator and static synchronous compensator in improving the voltage profile of the WECS. Further, fuzzy and fuzzy-sliding mode based UPFC controller is designed in order to improve the transient performance. Simulation results reflect the robustness of the proposed fuzzy-sliding mode controller for better reactive power management to improve the voltage stability in comparison with the conventional PI and fuzzy-PI controllers. In addition to this, system stability analysis is performed based on Eigen value, bode and Popov for supporting the robustness of the proposed controller.

KEYWORDS: *FACTS, UPFC, WECS, SCIG, VSC*

I. INTRODUCTION

Wind energy is one of the most efficient and promising renewable energy resources in the world, which is continuously growing with the increase of electrical power demand and the associated decrease in conventional resources of electricity resources. Depending on the control strategy, WECS are basically categorized into two types:

1) Constant speed or fixed speed WECS. This category incorporates squirrel cage induction generator (SCIG)
2) Variable speed WECS and this category includes two sub categories as:
(i) Full rated converter based WECS (Permanent Magnet synchronous generator)
(ii) Partially rated converter based WECS (Doubly fed induction generator)

Integration of wind energy sources (as a non-pollutant energy source) with electricity grid networks is necessary. On the other hand, the penetration of wind farms into the power system network can adversely influence the power system; specifically, due to the fluctuation nature of the wind speed, wind turbine generator tends to result in voltage fluctuations at the point of common coupling (PCC), which affects the voltage stability [5]. Moreover, another problem that may arise from the connection of wind farms into interconnected network is the system frequency oscillations due to insufficient system damping and/or violations of the transmission capability margin. If variable-speed wind turbines are employed, problems relating to harmonics will occur. One of the available solutions in regards to prevent the problems related to the integration of wind turbines with the exciting ac grid is using proper FACTS devices. Flexible alternative current transmission system (FACTS) technology plays an important role in improving utilization of existing power systems. They have been extensively used for effective power flow control and dynamic voltage support of systems. As a FACTS device, unified power flow controller (UPFC) allows system to be more flexible by using high-speed response active and reactive power compensations to improve the power flow of the transmission system. Thus, installing a UPFC at critical points of the transmission system will increase both the power dispatch (up to the power rating of existing generators and transformers) and the thermal limits of line conductors, by increasing the stability margin. Shunt and series converters of the UPFC can control both active and reactive powers smoothly, rapidly and independently in four quadrant operational moods.

The conventional controller such as PI controller is optimized only for single operating points and their performances are prone to parameter variations. The nonlinear characteristics of power system have great impact on the transient stability of the system and UPFC is also a highly nonlinear device, so a nonlinear control technique would be better to improve transient stability using UPFC. Sliding mode control (SMC) is nonlinear control technique which shows rapid response and immunity against operating point variations, and this control mechanism has been tested for UPFC to improve power oscillation damping, but it exhibits chattering effect and has been tested only for single operating point. The chattering effect caused by the SMC results in decreased control over the system and thermal losses in the electrical system. Keeping above points into consideration, this paper proposes the combination of fuzzy logic and SMC to achieve very fast control at every operating point without facing chattering effect. Recently also sliding mode controller has been implemented in UPFC to improve the power flow capability of power system in terminal sliding mode control as well as asymptotically sliding mode control has been proposed for power flow control, however this paper is silent about the variation of rotor angle under transient conditions.

II. Unified Power Flow Controller (UPFC)

A Unified Power Flow Controller (or UPFC) is an electrical device for providing fast-acting reactive power compensation on high-voltage electricity transmission networks. It uses a pair of three-phase control able bridges to produce current that is injected into a transmission line using a series transformer. The controller can control active and reactive power flows in a transmission line. The UPFC uses solid state devices, which provide functional flexibility, generally not attainable by conventional thruster controlled systems. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link. The main advantage of the UPFC is to control the active and reactive power flows in the transmission line. If there are any disturbances or faults in the source side, the UPFC will not work. The UPFC operates only under balanced sine wave source. The controllable parameters of the UPFC are reactance in the line, phase angle and voltage. The UPFC concept was described in 1995 by L. Gyugyi of Westinghouse. The UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system. Flexible AC Transmission Systems (FACTS) based power electronic converters like the UPFC are being used

extensively in power Systems because of their ability to provide flexible power flow control.
A schematic of the UPFC is shown in Fig.1.

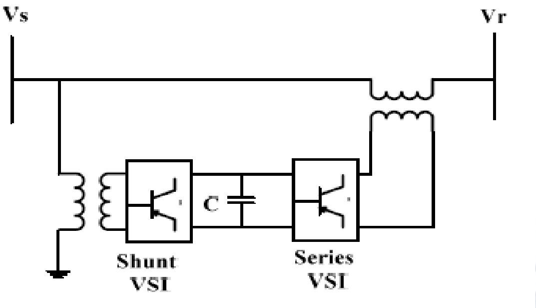


Fig.1. schematic of the UPFC

It consists of two voltage source inverter (VSI). One is a shunt VSI and the other is series VSI. The shunt and series VSI are connected via a DC link, which includes a DC capacitor (C). The shunt converter of UPFC controls the connected UPFC bus and DC capacitor voltage. The series converter of UPFC controls the line active and reactive power flow by injecting a series voltage of adjustable magnitude and phase angle.

III. STATCOM

The basic configuration of the STATCOM adopted in this work is shown in Fig.2.

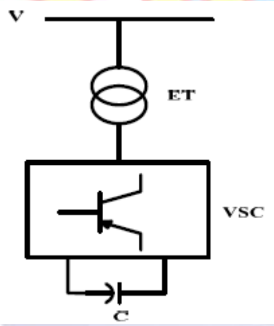


Fig.2. Schematic diagram of basic STATCOM

The voltage-source converter (VSC) is the basic electronic part of a STATCOM, which converts the dc voltage into a set of three-phase output voltages with desired amplitude, frequency, and phase. Fig. 3 shows the V–I characteristic of STATCOM.

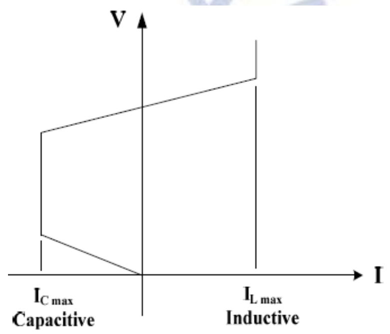


Fig.3. V–I characteristics of STATCOM

As shown in Fig. 2, the STATCOM can operate with its rated current even at reduced voltages. Hence, the injected reactive power varies linearly with the voltage. The effect of the STATCOM in this work is to inject reactive power into the grid when voltage drops as a result of a network short circuit (fault).

IV. MODELLING OF SMIB WITH UPFC

Fig. 4 shows the UPFC connected with the single machine infinite bus (SMIB) system Voltage at the generator terminal is V1∠δ, impedance of the timeline and series connecting transformer is rse+jxse, impedance of shunt connecting transformer is rs+jxs, and voltage at the bus is Vb∠θ. Current from the generator is Ise, current exchanged by shunt converter is Is and current flowing through series converter is I_b respective subscripts d and q represents the direct and quadrature axis components.

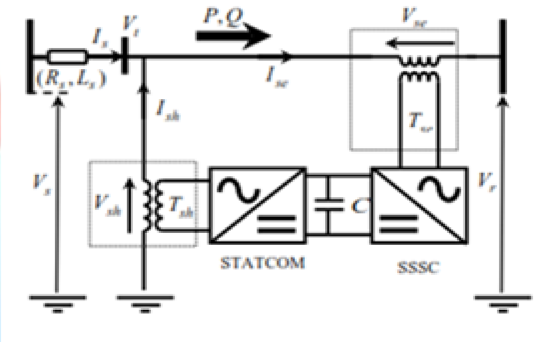


Fig.4. Basic power system with UPFC

Fig.5 shows the vector diagram of different voltages in d-q reference frame. The mathematical structure of SMIB with UPFC used in the paper is based on dq0 reference frame. With the higher modeling of synchronous generator, the accuracy of the system increases, but it also increases the system complexity.

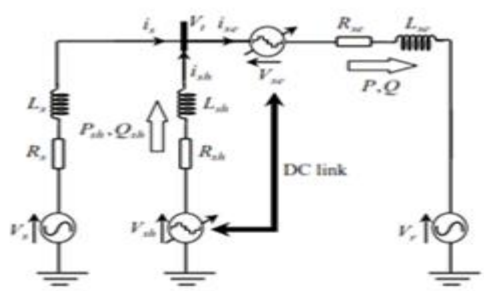


Fig.5. Single phase equivalent circuit of UPFC

With the higher modeling of synchronous generator the accuracy of the system increases, but it also increases the system complexity. So to maintain the required accuracy and avoid system complexities we have used fourth order model of synchronous generator, by neglecting the effect of the damper winding as illustrated in reference [10]. The generator data is taken from reference [11]. The expressions describing the behavior of the synchronous generator are given as follows:

$$\dot{\delta} = \Delta\omega \quad (1a)$$

$$\omega = \frac{\pi f_0}{H}(P_m - P_e) \quad (1b)$$

$$E_q' = \frac{E_{fd0} + \Delta E_{fd} - E_q' - (x_d - x_d')i_d}{\tau_{d0}'} \quad (1c)$$

$$\Delta E_{fd}' = \frac{-\Delta E_{fd} + K_e(V_{ref} - V_t)}{\tau} \quad (1d)$$

The UPFC is modeled with two voltage source converters(VSC) one in shunt and other in series with the tie line, both the converters are linked through a DC link capacitor, in order to maintain voltage support for the converters and provide independent control for real and reactive powers by the two converters.In UPFC both the converters are able to exchange real and reactive power with the power system, but in our system we have used series converter to exchange the real and reactive power and shunt converter has been used to exchange the real power demanded or absorbed by the series converter to keep the DC link capacitor voltage constant. The mathematical structure for the UPFC has been used as described in reference and is given as follows:

Shunt Converter

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \frac{-r_s}{L_s} & \omega \\ -\omega & \frac{-r_s}{L_s} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix}\begin{bmatrix} V_d - e_{sd} \\ V_q - e_{sq} \end{bmatrix} \quad (2)$$

Series Converter

$$\frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} = \begin{bmatrix} \frac{-r_{se}}{L_{se}} & \omega \\ -\omega & \frac{-r_{se}}{L_{se}} \end{bmatrix}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{se}} & 0 \\ 0 & \frac{1}{L_{se}} \end{bmatrix}\begin{bmatrix} V_d + e_{sed} - V_{bd} \\ V_q + e_{seq} - V_{bq} \end{bmatrix} \quad (3)$$

Where $i_d = i_{sd} + i_{sed}$ and $i_q = i_{sq} + i_{seq}$ (4)

The DC link capacitor voltage dynamics has been established on the basis of power balance on the DC side of the converters. The net real power exchanged by both the converters through DC side should be zero to keep the capacitor voltage constant.

The voltage dynamics across the capacitor is given as:

$$\frac{d\dot{V}_{dc}}{dt} = \frac{(V_d * i_{sd} + V_q * i_{sq}) - (e_{sed} * i_{sed} + e_{seq} * i_{seq})}{C * V_{dc}} \quad (5)$$

Steady state equations used in the system are:

$$E_q' = V_q + X_d' * i_d \quad (6)$$

$$E_{fd} = E_q' + (x_d - x_d') * i_d \quad (7)$$

$$i_{sd} = i_s \cos\delta \quad (8a)$$

$$i_{sq} = i_s \sin\delta \quad (8b)$$

$$\delta = \tan^{-1}(V_d / V_q) \quad (9)$$

$$V_{bd} = e_{sed} + (x_q + x_{se}) * i_q - x_{se} * i_{sq} \quad (10a)$$

$$V_{bq} = e_{seq} + E_q' - (x_d' + x_{se}) * i_d + x_{se} * i_{sd} \quad (10b)$$

A. Sliding Mode Control

The sliding mode control is popular nonlinear control technique which is known for its robustness against parameter variations. The SMC based controller brings the system to steady state by sliding the state trajectory along the sliding surface and reducing the error value to zero, when the state trajectory reaches to origin. This sliding surface is usually defined by using the error and its derivative as in (12).

$$e = y_{ref} - y_{actual} \quad (11)$$

$$s = e + k\dot{e} \quad (12)$$

To get obtain an attractive surface the dynamics usually chosen is

$$\dot{s} = m.\text{sign}(s) \quad (13)$$

Since, the switching caused by the *signum* function is hard one we replace it by tanh function to make the controller output smoother as shown in the Fig. 6.

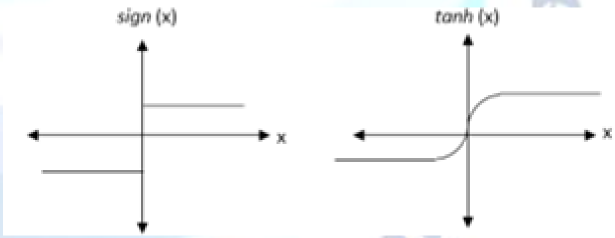


Fig 6. Outputs of signum and tanh function.

$$\tanh(x) = \begin{cases} \text{sign}(x) \text{ if } |x| \geq 1 \\ x|x| + 2x \text{ if } |x| \langle 1 \end{cases} \quad (14)$$

So the controller output would be:

$$u = m.\tanh(s) \quad (15)$$

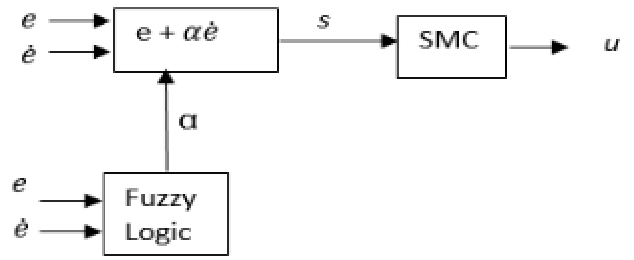
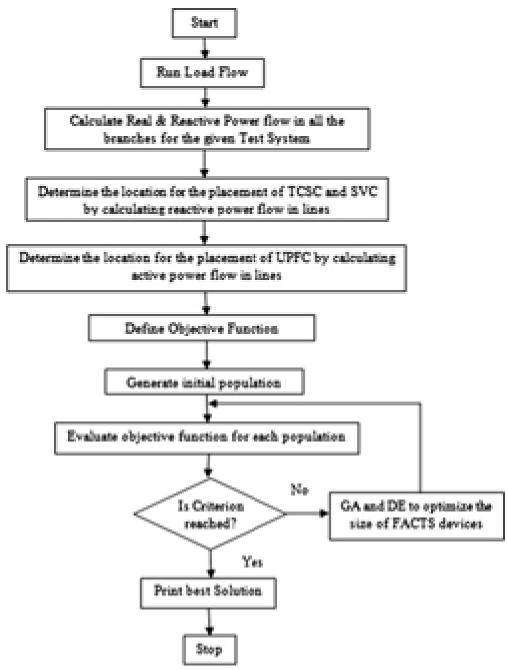


Fig.6. Control structure for the Fuzzy-Sliding Mode Controller

The fuzzy logic component of the controller works to alter the slope of the sliding surface in accordance with the state errors to make the response faster and bring the system to steady state rapidly. In this way the controller need not to wait for the state error to reach the sliding surface rather the sliding surface moves towards the state error, so that the errors only need to slide over the surface and reach zero. Once the Fuzzy logic has done its job the SMC unit makes the state errors to slide along the surface to reach zero. The fuzzy logic unit takes state error e and its derivative with respect to time, to determine the position of the state error relative to the sliding surface and output of the fuzzy logic is the required updated slope (a) for the sliding surface.

ALGORITHM



A. **Real Power Flow Control**

The real power control is achieved by the series converter of the UPFC, to stabilize the real power flow through generator; controller takes the rotor speed deviation as error during sudden transients. Corresponding to this error the FSMC controls quadrature axis component of the voltage injected by the series converter, which in turn enhances the real power flow in the line.

B. Reactive Power Flow Control

The reactive power control is achieved by the series converter of the UPFC, to stabilize the reactive power flow through generator; controller takes the deviation of reactive power flow from the reference value as error during sudden transients. Corresponding to this error the FSMC controls direct axis component of the voltage injected by the series converter, which in turn manages the reactive power flow in the line.

C. DC Capacitor Voltage Control

The DC link capacitor voltage is maintained at a constant value by the shunt converter. It absorbs or supplies the real power to the DC capacitor as needed by the series converter to maintain the power balance on the DC side. It takes the deviation of the capacitor voltage from the reference value as error and corresponding to this error the FSMC regulates the current exchanged by the shunt converter.

V. SIMULATION AND RESULT

The ability of the Fuzzy Sliding Mode Controller with UPFC to damp the transient power oscillation is analyzed by inducing three phase fault near the generator terminal for 120milliseconds. This assessment has been carried out for three different power levels to establish the robustness of the controller. Due to the fault the voltage reduces to a critical value and the power flow in the system is hindered which leads to the transient oscillation in the power system. All the values are taken in per unit system during modeling and simulation.

The project has been implemented using Matlab & Simulink.

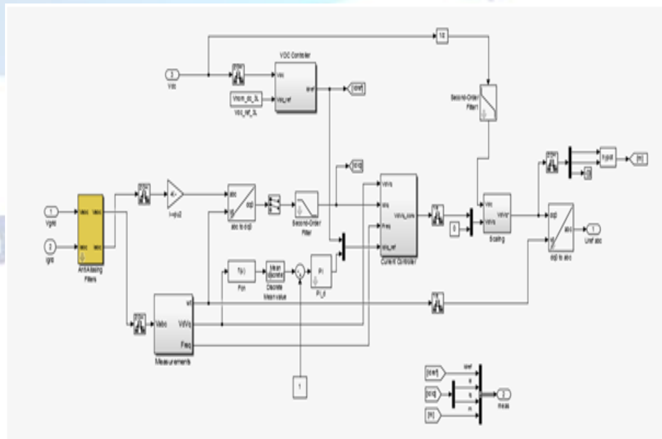


Fig SEC Control System

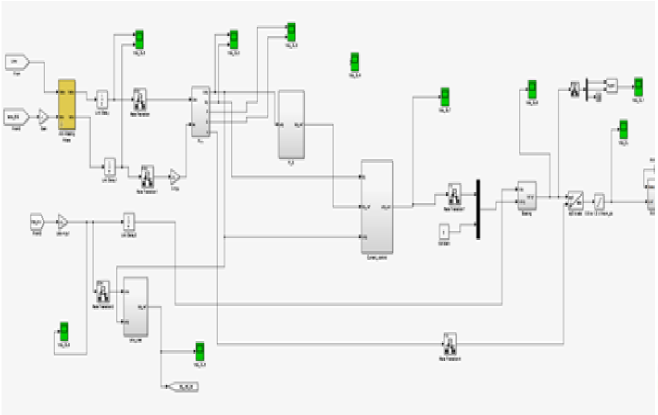
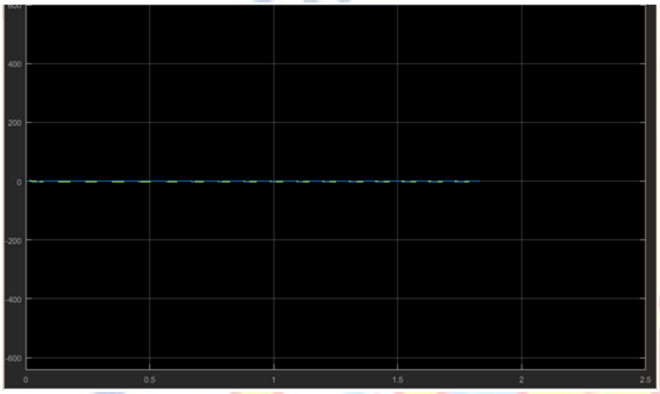
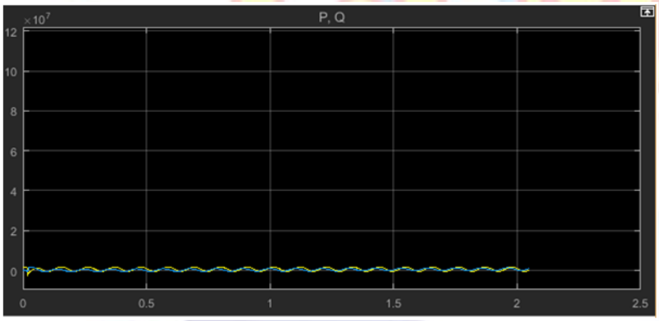


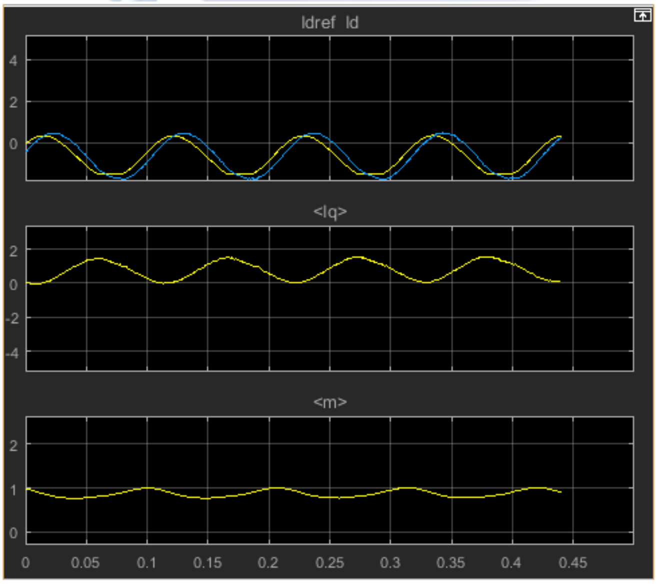
Fig REC Control System



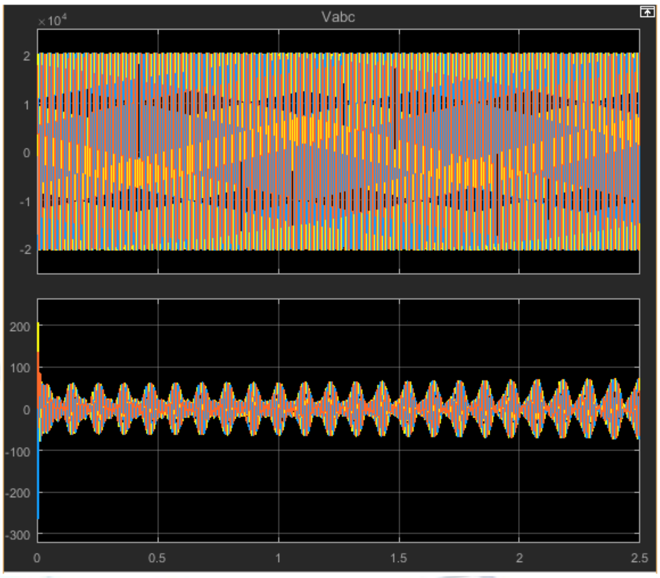
Vdc_3LggH



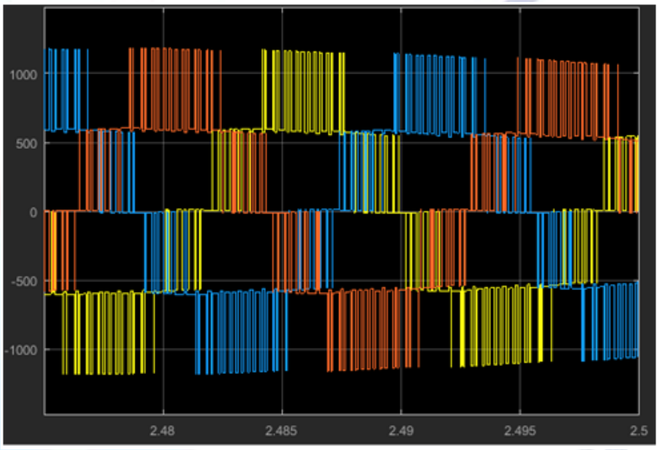
PQ_Grid



3L_Rectifier control



VI Grid



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VI. CONCLUSION

In this paper, effects of the STATCOM and UPFC on the performance of FSWT have been by MATLAB. The simulation results show that the UPFC prevents the voltage dip during a fault and restores the voltage after the fault clearance using a shunt inverter. In addition, it improves generator speed and the voltage stability of power grid integrated with WECS.

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