Switching Level Modeling and Operation of Unified Power Flow Controller

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Abstract - This proposed work aims at forming a switching level modeling of Unified Power Flow Controller (UPFC) and analyzing its operation. The switching level modeling of UPFC is carried out using high power electronic devices such as IGBT based six pulse shunt and series converters. The operating performance of UPFC is demonstrated on Single Machine Infinite Bus (SMIB) system for different case studies. The real and reactive power tracings in the system are obtained by varying the firing angle of shunt converter and modulation index of the series converter. The simulation study is carried out in MATLAB/Simulink environment. The proposed topology effectively controls the real and reactive power flow in the transmission lines. The proposed model considerably improves the system stability by damping the oscillation during the vulnerable conditions.

Keywords - SMIB, switching Level Modeling, unified power flow controller

I. INTRODUCTION

The increasing demand and complexity in AC power networks requires a high performance power flow control system to maintain the desired power flow and to enhance static and dynamic stability. The evolution in power electronic devices along with the development and control have allowed the design and implementation of structural controllers known as Flexible AC Transmission System (FACTS), which are emerging as feasible technology for the improvement of system's dynamic behavior. The benefits arising from FACTS devices are widely appreciated. The concept of Flexible AC Transmission System (FACTS) was introduced [1,2] as a family of power electronic equipments which have emerged for controlling and optimizing flow of electrical power in the transmission line. The concepts of Unified Power Flow Controller (UPFC) its performance and steady state characteristics have been widely reported in the literature [3, 4]. The UPFC has been researched broadly and many research articles dealing with UPFC modeling, analysis, control and application have been published in the recent years. Mathematical models were developed for UPFC to determine steady state operational characteristics using state space equations without considering the effects of converters and the dynamics of generator [5, 6]. The performance of UPFC was analyzed by designing a series converter using conventional and advanced controllers [7, 8]. Mathematical model of UPFC using general PWM and space vector approach was used to perform the power flow studies, eigen analysis and transient stability investigations [9].

A non linear dynamic small signal model of network with UPFC was established for transient studies. The model evaluated the compensation effects of UPFC, optimized the location of UPFC and its control design [10]. An equivalent two bus power network was developed based on sets of equations for a system including the UPFC was proposed. This provided a useful tool to rate; evaluate the performance of UPFC on power systems [11].

The analysis based on mathematical model of UPFC was simplified by incorporating the voltage source model with generator output power equation and thereby the dynamic analysis of the system was simplified. The UPFC model can also be used to represent the system with STATCOM or SSSC [12].The mathematical model of vector controlled UPFC was derived and a vector control system was developed for each of the UPFC operation modes are identified. In this vector control analysis three phase variables were converted into vectors with synchronously rotating D-Q axis system which simplifies the analysis and control of polyphase AC networks. The paper also indicates that a UPFC can be controlled independently the real and reactive power in the transmission line by controlling the basic parameters such as transmission line impedance, transmission line voltage [13].

The analysis on inclusion of PWM AC link UPFC into a power flow program was discussed, taking into account a novel Γ controller and the PWM Series compensator. The system was configured by shunt phase shifting transformer (SPT), Filter capacitor (FC), a quadruple-throw single pole three phase vector switching converters (VeSC) and a series injection transformer (SIT). The PWM series compensator was connected to power system to regulate the active power flow on the corresponding transmission line [14]. The UPFC was modeled as IGBT multi pulse converters using PWM control connected in series with the system. The impact of real and reactive power flows through the parallel transmission lines were analyzed by varying the modulation index and phase angle of the inverter. The effect of connecting a shunt converter to inject the reactive power into the system has not been analyzed [15].

A new non linear controller was designed for UPFC to damp out the active power oscillations in the system during fault conditions. The performance of controller was compared with PI controller to show its superiority for maintaining the stability [16].

A controller design was implemented to control series injected voltage and shunt injected current for UPFC using simplified models and the performance were calculated. The shunt and series device of UPFC was modeled as two twelve pulse converters with its controllers. A modulation controller which supplements the real power controller is incorporated to bring vast improvement in transient stability and damping [17]. A novel control technique was

developed to achieve the maximal improvement in transient stability & damp the rotor oscillations using UPFC. A control strategy was brought about by selectively operating the UPFC to maximize or minimize the power flow in the line in which it is located. The simulation is carried out using Simulink and Matlab optimization tool box [18]. The UPFC controller includes series controller, shunt controller and DC bus voltage controller. The performance of PI control with UPFC was demonstrated through different case studies taking into account the impedance of series transformer and effect of transmission line charging [19]. The UPFC was modeled as a back to back connection of shunt and series converter using hysteresis current forced and PWM control respectively. The steady and dynamic state stabilities were analyzed by varying the modulation index and phase angle of the series inverter [20].

A sensitivity based approach has been developed for finding the optimal location of UPFC when the system is subjected to congestion. In normal condition the location of UPFC can be decided on minimization of real power loss and cost of the UPFC that depends on its control parameters. In a congested system the location of UPFC can be found based on the real power flow performance index (PI). The UPFC was implemented and demonstrated on various standard test systems and the minimization of real power loss and improvement in voltage profiles are narrated [21].

The UPFC was designed with IGCT based three voltage source inverters with common DC link. The UPFC was installed at the midpoint of the transmission line which is known as centre node UPFC(C-UPFC).Out of three converters one of the converters was connected in parallel at the midpoint of the line, and the other two converters are connected in series. To show the regulation of voltage, real and reactive power flow at the midpoint of the transmission line, the C-UPFC was tested on two machine bus system using PSCAD/EMTDC [22].

The UPFC was modeled as voltage source model and PWM switching level model. The voltage source model of UPFC was constructed with equivalent voltage source and impedances using MATLAB. The switching level model of UPFC was designed and simulated in EMTP.The equivalent impedance of voltage source model was found from the dynamic responses of UPFC switching level model. The results show that switching level model was more accurate than voltage source model [23]. The optimal location and equivalent impedance of UPFC are found by voltage source model and switching level model by varying the amplitude and phase angle of injected voltage [24].In laboratory implementation of FACTS devices, UPFC was setup by PWM modulation controllers which provides more effective control of real and reactive power flow [25]. The Multi Input Multi Output (MIMO) non linear problem of a power transmission system was analyzed with UPFC using multivariable control technique. To show the independent control of real and reactive power flows the feedback linearization control (FBLC) scheme for UPFC was implemented in a scaled down laboratory model using DSP TMS320LF2407A.The FBLC based UPFC was compared with PI controlled UPFC to

show its superiority for damping of power oscillation, for the SMIB system with two identical parallel lines [26].

However, there have been very few theoretical studies on firing angle control of shunt converters in the UPFC and their effects in the power system have not been analyzed in detail. Hence in this paper, the proposed technique aims at to control the real and reactive power flow in the transmission lines, by effectively varying the firing angle of shunt converter and modulation index of the series converter.

In this paper dynamic control of UPFC is analyzed with six pulse converter using switching level model. The architecture of the paper in Section II explains the proposed model of UPFC, section III describes the modeling of UPFC, and section IV provides the simulation results and analysis. The conclusion is summarized in Section V.

II.   PROPOSED MODEL OF UPFC

An infinite bus is a source of constant frequency and voltage either in magnitude or angle. Single Machine Infinite Bus System (SMIB) equipped with a UPFC is connected to the remote system through a transformer and a transmission line having two "π" section models as shown in Fig. 1(a). A UPFC is placed in the transmission line at point m (between middle of two line sections m-n) in the system. The reactance of various components of the system is shown in Fig. 1(b). The phasor of Series injected voltage and shunt injected current of the UPFC is shown in Fig. 1(c).
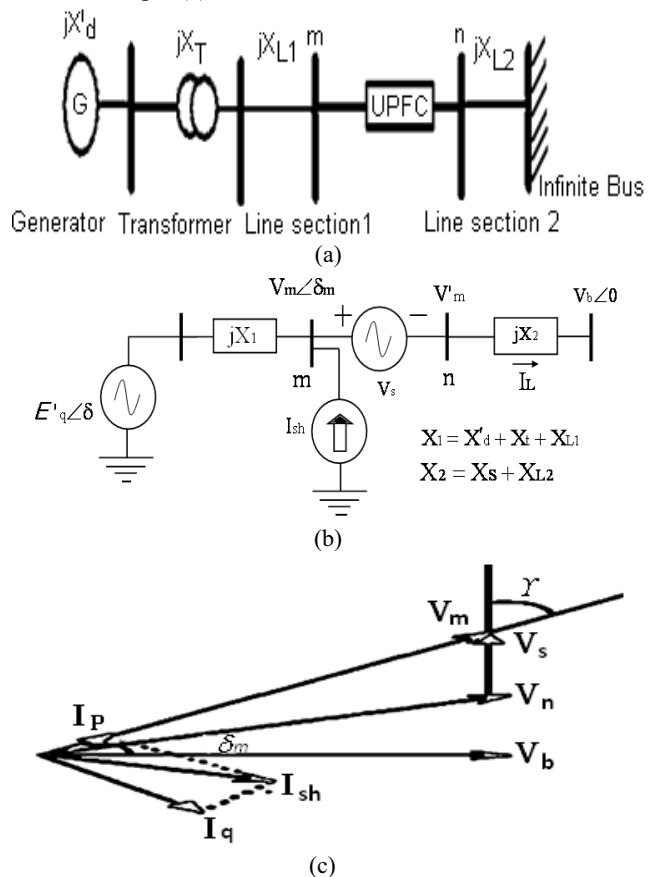

(a)

$$X_1 = X'_d + X_t + X_{L1}$$
$$X_2 = X_s + X_{L2}$$

(b)

(c)

Fig. 1(a): Single line diagram (b) reactance diagram
(c) Phasor diagram of UPFC

A. *Control Scheme for UPFC*

The linear firing angle and sinusoidal pulse width modulation have been proposed as the switching schemes for shunt & series converters.

The primary advantages of the proposed controllers are

- It works a wide range of operating conditions.
- Ability to pass the real power flow bi-directionally.
- Maintaining well regulated DC voltage.
- Independent of load & system parameters.

B. *Shunt Converter Control*

The shunt converter consists of six IGBT switches can be controlled by linear firing angle control scheme produced by the linear angle PWM Modulator. The pulse width modulated (PWM) control, the converter switches are turned on and off several times during half cycle and the output voltages is controlled by varying the width of the pulses.

The PWM pulse can be generated by comparing the saw tooth waveforms with the control signal $V_{control}$ as shown in Fig.2. The frequency repetitive wave form with constant peak which is shown to be sawtooth, established the switching frequency as 60 Hz. This frequency is kept constant in a PWM control. The delay angle α with respect to the positive zero crossing of the ac line voltage is obtained in terms of $V_{control}$ and the peak of the saw tooth waveform V_{st}. The firing angle can be calculated as,

$$\alpha = 180\,° \times \frac{Vcontrol}{Vst} \qquad (1)$$

The firing angle is varied from 0 to π.The PWM modulator will generate the gating pulse for IGBT 1.The IGBT T1 is fired at $\omega t = \frac{\pi}{6} + \alpha$ .The remaining IGBT'S are fired at an interval of $\pi/3$.By varying the firing angle α the DC voltage can be found as (27)

$$V_{dc} = \frac{3}{\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} V_{ab}d(\omega t) \qquad (2)$$

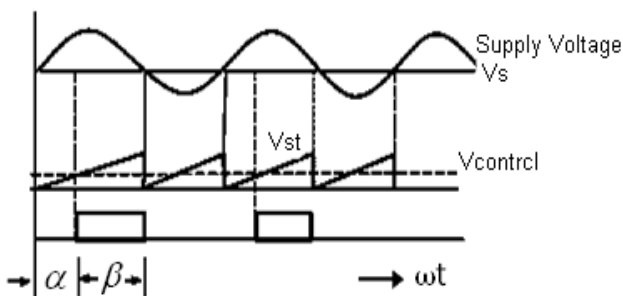$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} \cos\alpha \qquad (3)$$

Fig. 2: Generation of PWM pulses for Shunt converter

C. *Series Converter Control*

The series converter can be controlled by sinusoidal pulse width modulation scheme (SPWM). The generations of SPWM firing pulses for inverter as shown in Fig.3.The gating signals are generated by comparing three sinusoidal reference signals which are phase shifted by 120˚, with a triangular carrier wave frequency of f_c to generate the gating pulse for each phases. The frequency of reference signal f_r determines the inverter output frequency f_o and its

peak amplitude A_r, controls the modulation index M, and then in turn the rms output voltage v_o. The modulating frequency of the inverter can be found by the following formula as

$$mf = \frac{f_c}{f_r} \qquad (5)$$

In this control the modulating frequency taken as 18, the reference signal frequency is 60 Hz and carrier frequency is 1080 Hz. In SPWM control, the converter switches are tuned on and off several times during a half cycle and the output voltage is controlled by varying the width of pulses. For each phase if δ_m is the width of the mth pulse, the rms AC output voltage v_o can be computed as

$$vo = vs\left(\sum_{m=1}^{p} \frac{\delta m}{\pi}\right)^{\frac{1}{2}} \qquad (6)$$

This technique is simple, control is very fast, and device current is directly limited. The distortion factor and lower order harmonics are reduced significantly compared with other PWM modulations. The advantage of this unipolar SPWM modulation is less switching stress ($\pm 0.5V_{dc}$) on devices and it will eliminate the condition that two switching devices in the same arm cannot conduct at the same time.
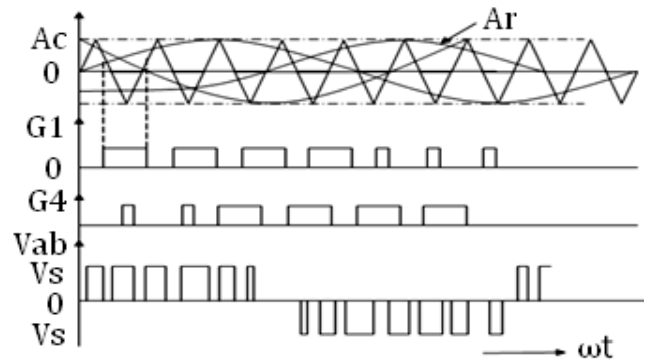

Fig. 3: Generation of SPWM Firing Pulses for Series converter

III. MODELING OF UPFC

This paper describes the switching level modeling of UPFC using IGBT. The performance of UPFC is demonstrated on SMIB system & real and reactive power flow tracings are obtained. The UPFC is composed of two back to back PWM Converters connected by a common DC link. This modeling is done with Simulink blockset and simulation is carried out in MATLAB environment as shown in Fig.4. The system circuit parameters are given in appendix.

A. *Simulation Model*

The synchronous generator is connected to the linear load through the Power transformer and "π"section model of transmission line. The UPFC is located at the middle of the transmission line. The shunt device of UPFC consists of three phase IGBT converter with linear angle controller. The shunt converter is connected to the transmission line in parallel through a three phase transformer. The series device of the UPFC consists of three phase IGBT inverter with SPWM controller. The series converter is connected to the transmission line in series through three single phase

transformers. The IGBT firing pulses are generated for shunt & series converters as described earlier in section (2). By varying the firing angle (α) to DC voltage is controlled accurately. The inverter output voltages are effectively controlled by varying the modulation index (M).

Cases studied:

The following three case studies are simulated on SMIB system and the results are analyzed as follows.
  (i)   Base load condition
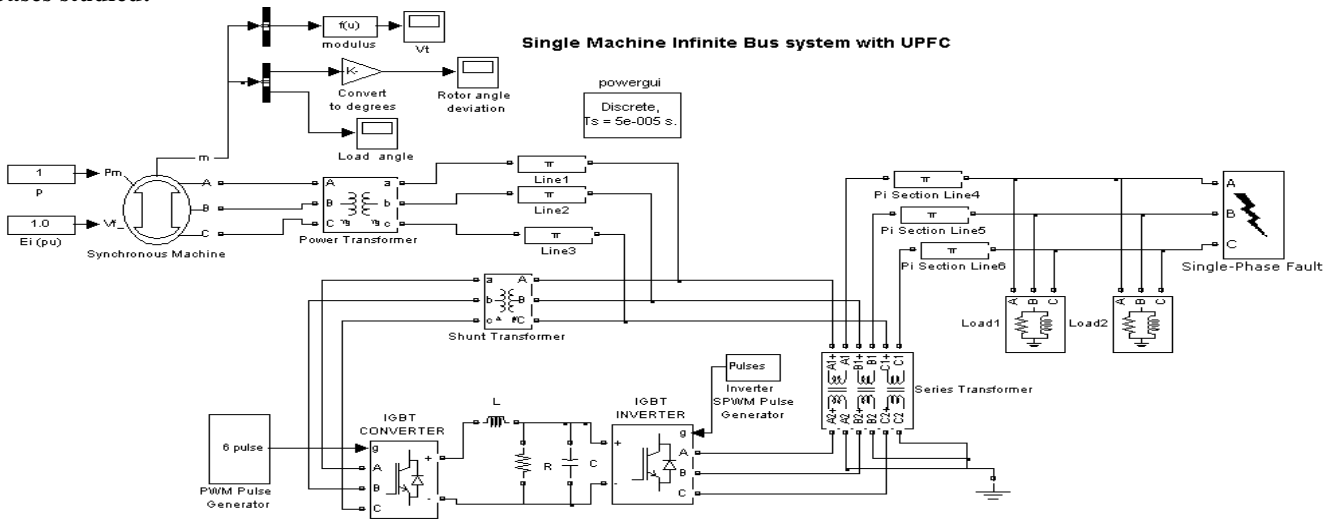 (ii) Increased load condition
  (iii) Fault condition

Fig.4: Switching level model of Unified Power Flow controller (UPFC)

IV. RESULT ANALYSIS

Case (i)

In this case, the SMIB is connected with 75% base load condition. The real and reactive power tracings are obtained through simulation and their magnitudes are given in Fig. 5(a). After the insertion of UPFC, its firing angle is varied to enhance the power flow in the system. The power tracings are obtained with constant modulation index is shown in Fig. 5 (b).
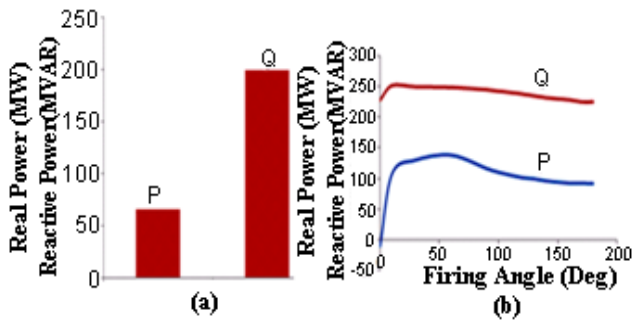

Fig 5: (a) Real & Reactive power flow without UPFC
(b) Real & Reactive power flow with various firing angles

Real power variation of shunt converter, series converter,DC capacitor and the transmission lines by installing the UPFC as shown in Fig. 6(a).The output power of the shunt converter is varied by varying the firing angle of the individual IGBT's and power tracings are obtained for both the converters. It clearly explains that the real power flowing through the transmission line is increased by the summation of real power supplied by the shunt converter, series converter and power across DC link capacitor. Reactive power variation of shunt converter, series converter and the transmission lines by inserting the UPFC as shown in Fig. 6(b).
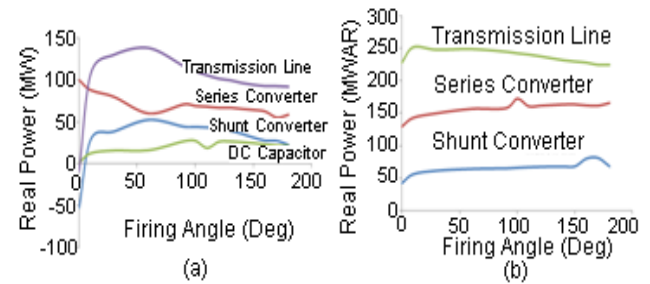

Fig. 6: Distribution of Power by the UPFC (a) Real power
(b) Reactive power

After inclusion of UPFC the reactive power of the line is increased by the summation of reactive power supplied by the shunt and series converter.

The real & reactive power flow tracings for various modulation index of the UPFC with constant firing angle are obtained as shown in Fig 7. It illustrates that the magnetizing power shows stronger control over the real power by the inclusion of UPFC.
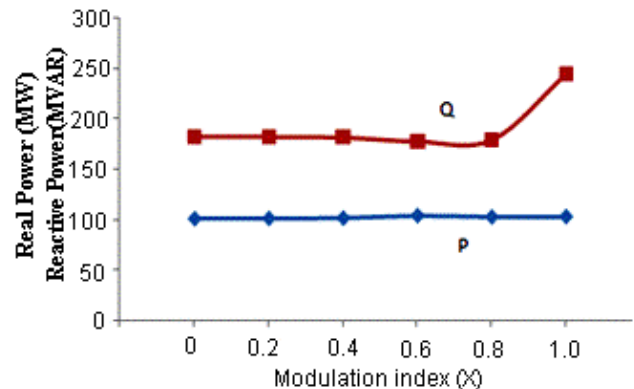

Fig 7: Real & Reactive power flow with various Modulation index

The harmonics analysis of the line current using Fast Fourier transform (FFT) window by Simulink as shown in Fig.8.The fundamental harmonics are high and odd harmonics are reduced within acceptable limits.
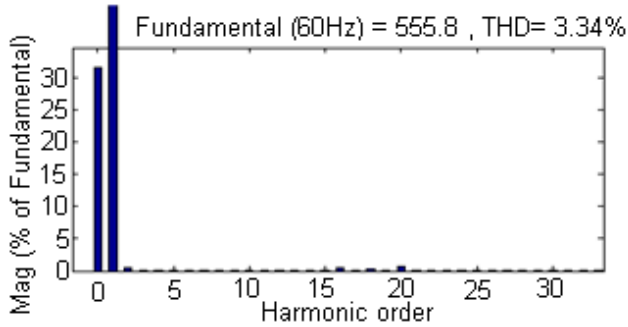

Fig. 8:Total Harmonic Distrotion of line voltage

Case (ii)
In this case, the SMIB system is connected with increased in load condition (125% of base load). Before inserting the UPFC the magnitudes of real and reactive power tracings are obtained through simulation as shown in Fig. 9(a). After the insertion of UPFC, the power tracings are observed for various firing angle with constant modulation index as shown in Fig. 9(b). It is inferred from the figure that when the firing angle is varied from 90°to 180°, the real and reactive power flows are effectively controlled. It shows that the driving power of UPFC is increased to increase the generation capability
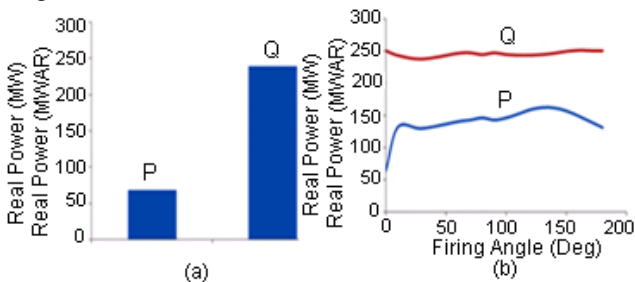of generator.

Fig. 9(a): Real & Reactive Power flow without UPFC   (b)
Real & Reactive power flow with UPFC

Case (iii)
To illustrate the performance of UPFC in the transient conditions, a transmission fault is created at load end of the SMIB system.
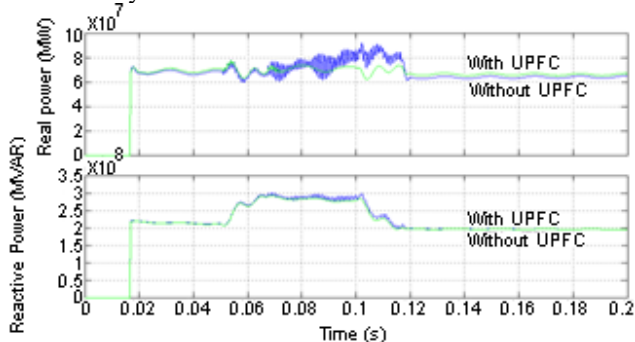

Fig. 10: Real & Reactive power flow before & after connecting the UPFC during fault

The fault is cleared at 0.1 seconds. The real & reactive power flows through the transmission line during the fault condition are obtained through the simulation study.

The Fig. 10 shows that the variation of real & reactive power flow before & after connecting UPFC. After compensation, the real & reactive power flows are stabilized. The UPFC will produce stable state within half of the time in the fundamental frequency. The variation of line voltage and current before and after inserting the UPFC is obtained to illustrate its impact. The corresponding voltage and current wave forms are given in the Figures 11 & 12.
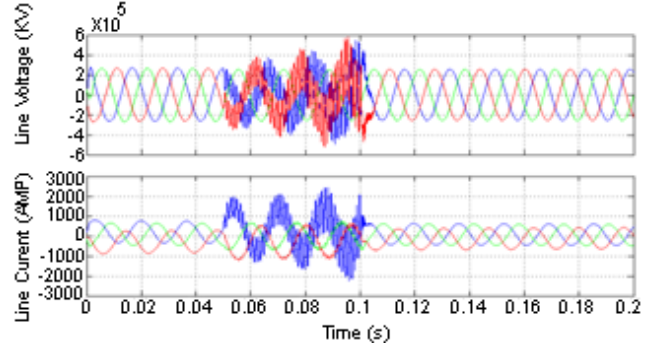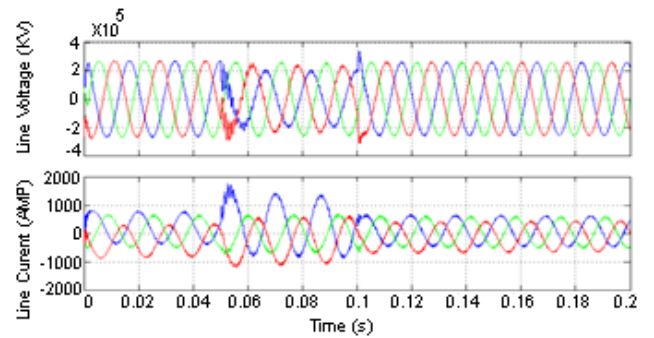

Fig. 11: Line voltage & line current without UPFC

Fig. 12: Line voltage & line current with UPFC

The simulation results of generator dynamics after inclusion of UPFC are illustrated in Fig.13. The illustration describes the generator terminal voltage and load angle are stabilized. From the figure it is inferred that the system maintains the stability & increases the loadabilty of the generator.

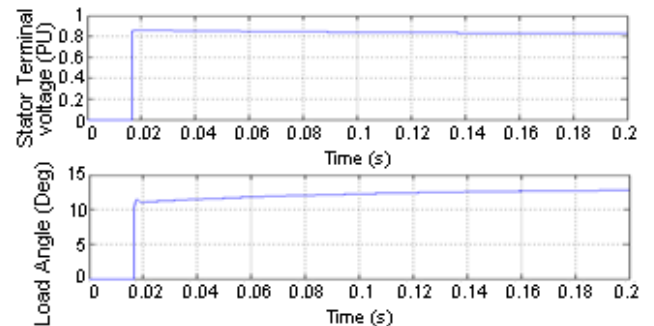Fig.13: Simulation results of terminal voltage and load angle of generator

V.   CONCLUSION

In this paper, the simulation results of switching level modeling of UPFC using IGBT developed in MATLAB/SIMULINK have been presented. The linear firing angle and sinusoidal pulse width modulation have been proposed as the switching schemes for shunt & series converters. These switching schemes have been

implemented in the developed UPFC model & the performance is demonstrated on SMIB system using simulation in MATLAB. The simulation result proves that the UPFC with the proposed switching schemes functions successfully as the real time power flow controller. This controller improves the performance of transient and dynamic stability and achieves good damping of power and voltage oscillations in the system.

Appendix **Table: 1 Simulation system parameters**

Sl.no	Simulation system parameters	Design values
	Synchronous Generator	3 phase
1.	Rated voltage	13.8 kV
2.	Rated power/Frequency	200MW/60Hz
3.	X/R Ratio	3
4.	Terminal voltage Magnitude	1.0
5.	Resistance Rs	0.003 Ω
6.	Leakage Inductance Lls	0.1983 H
7.	D-axis magnetizing inductancesLmd	0.91763 H
8.	Q-axis magnetizing inductancesLmq	0.21763 H
9.	Field Resistance Rf	6.358e-4 Ω
10.	Leakage Inductance Llfd'	0.16537 H
11.	D-axis Damping resistance Rkd	4.6454e-3Ω
12.	Q-axis Damping resistance Rkq1	6.8430e-3Ω
13.	Damping leakage inductance D-axis/Q-axis(Llkd/ Llkq1)	3.920e2/ 1.454e-2H
14.	Inertia coefficient H (s)	3.195
15.	friction factor F (pu)	0
16.	number of pole pairs p	32
17.	initial speed deviation Δω	0
18.	Rotor electrical angle Θ (deg)	12
	Power transformer (Υ/Δ)	
19.	Nominal power	200MVA
20.	Primary/Secondary voltage	13.8/230kV
21.	Magnetization resistance/reactance	500/500
	Transmission line	
22.	Resistance	0.01PU/km
23.	Inductive /capacitive reactance	0.1/0.1PU/km
24.	Length of transmission line	2x100km
25.	**Shunt & series Converter** power	100MVAR
26.	DC link capacitor C1=C2	2000 microF
	Shunt transformer	
27.	Nominal power	100MVA
28.	Rated voltage	230/25 kV
	Series transformer	
29.	Nominal power	100MVA
30.	Primary/Secondary voltage	14/10 kV
31.	**Converter IGBT** Snubber resistance	100 Ω
32.	Snubber capacitance	0.1e-6
33.	Internal resistance	1e-3 Ω
34.	**Inverter IGBT** Snubber resistance	10000 Ω
35.	Snubber capacitance	inf
36.	Internal resistance	1e-4Ω

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