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Real and Reactive Power Control by using 48-pulse Series Connected Three-level NPC Converter for UPFC

A. Naveena
Department of EEE, GMRIT, Rajam, allumalla.naveena@gmail.com

M. Venkateswara Rao
Department of EEE, GMRIT, Rajam, mvrgmrit@yahoo.co.in

Real and Reactive Power Control by using 48-pulse Series Connected Three-level NPC Converter for UPFC

A.Naveena[1], M.Venkateswara Rao[2]
Department of EEE, GMRIT, Rajam
Email id: allumalla.naveena@ gmail.com, mvrgmrit@yahoo.co.in

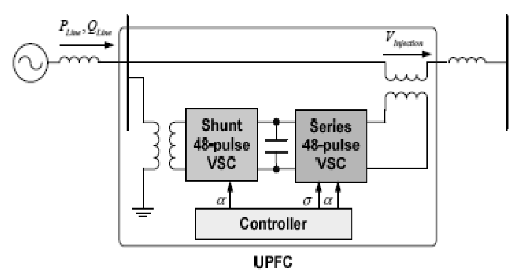
Abstract--- The equipments based on the power electronics have been improved under the name of Flexible Alternating Current Transmission Systems (FACTS) in the last years. Unified Power Flow Controller (UPFC) is the most widely used FACTS device to control the power flow and to optimize the system stability in the transmission line. UPFC is a FACTS devices that can control active and reactive power flow in transmission line by means of injection controllable series voltage to the transmission line. This paper proposes a new connection for a Unified Power Flow Controller (UPFC) to control the active and reactive power flow control in two sides of a transmission line independently and it regulates bus voltage in the same transmission line, furthermore it is possible to balance line current too. This connection of the UPFC will be called an center node UPFC (C_UPFC). It is one of the newest devices within the FACTS technology. The structure and capability of the C_UPFC is discussed and its control scheme is based on the d-q orthogonal coordinates. According to this, the performance of UPFC for several modes of operations using different control mechanisms based on Proportional-Integral (PI) and PID based controllers has been studied. The obtained simulation results from Matlab/simulink confirm the effective features.

Keywords: Center Node Unified Power Flow Controller (C_UPFC) model, real and reactive power, Flexible AC Transmission System (FACTS), 48- Pulse GTO, Neutral Point Clamped (NPC) converter, angle control.

1 INTRODUCTION

The static series synchronous compensator (SSSC) can control active and reactive in a transmission line in a small range via storied energy in capacitor DC-link where static synchronous compensator (STATCOM) with injecting reactive power can regulate the bus voltage in a transmission line. Unified Power Flow Controller (UPFC) is the most versatile and complex Flexible AC Transmission Systems (FACTS) equipment that has emerged for the control and optimization of power flow in power transmission systems [1-3]. It has the combining features of both series converter and shunt converter based FACTS devices, and is capable of realizing voltage regulation, series compensation, and phase angle regulation at the same time. Therefore, the UPFC is capable of independently controlling the active power and reactive power on the compensated transmission line [4, 5].
The electric utilities are continuously looking for new devices that will enable interconnected systems to have increased power transfer abilities with transmission lines. UPFC and IPFC are FACTS devices that can control the power flow in transmission line by injecting active and reactive voltage component in form series to the transmission line. The UPFC is a flitting multi-purpose FACTS device that extends their capability to inject shunt current or series voltage that involve real power flow as well With UPFC, the real and reactive power can be controlled independently. The unified power flow controller is capable of controlling all the power system parameters such as voltage magnitudes, phase angles, and effective line impedance simultaneously consists of two voltage-source converters (VSCs) that are connected to a common DC- link. One of the VSCs is connected in series with a transmission line while the other one is connected in shunt with the same transmission line. The DC bus of both VSCs are supplied through a common DC capacitor, hence UPFC combines the functions of a STATCOM and a SSSC. STATCOM maintains constant the bus voltage and provide energy for DC link of SSSC and it can regulates capacitor's voltage of DC-link, SSSC with injection controllable voltage controls the active and reactive power flow control in the transmission line.
Most existing Voltage Source Converter (VSC) based FACTS devices rated above 40 MVar use multipulse converters [6]. The 48-pulse VSC based on 3-level NPC converters has been used in UPFC due to its near sinusoidal
voltage quality of <1% voltage THD. The 48-pulse VSC has been implemented with ratings up to 100 MVA [7, 8]. This paper applies the 48-pulse series connected three-level NPC converters in both shunt and series converter of UPFC. The coordinated control and operation of shunt and series converters are investigated. The UPFC system with shunt and series three-level 48-pulse Gate Turn-off Thyristor (GTO) converter is implemented in Matlab/Simulink. A new "angle control" scheme is designed for the series 48-pulse converter used for UPFC application. The UPFC operation boundary in terms of real and reactive power is specifically investigated.
The simulation results evaluate the performance of the UPFC connected to the 500-kV grid with the proposed controller.

II. PRINCIPLE OF UPFC



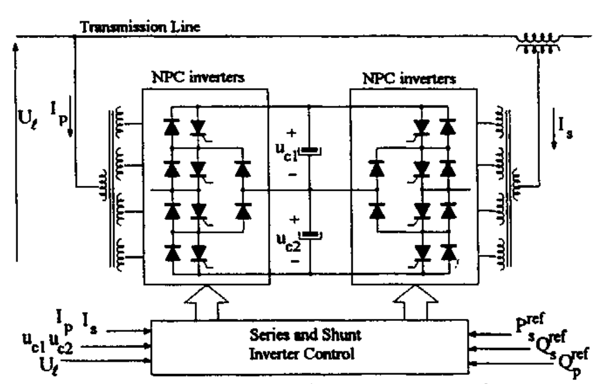


Fig.1 - Simplified diagram of UPFCs with NPC inverters

A simplified schematic of a UPFC system is shown in Fig 1. The UPFC consists of two 48-pulse series connected 3-level NPC inverters, one connected in series with the line through a series insertion transformer, and another connected in shunt with the line through a shunt transformer. The DC terminals of the two supported by a capacitor bank.

The series inverter controls the magnitude and angle of the voltage injected in series with the line. The series inverter exchanges real and reactive power with the line. The reactive power is provided by the series inverter itself, and the real power is transmitted from the DC terminals. The shunt inverter demands the real power needed by the series converter from the line. Meanwhile, the shunt inverter also exchanges (capacitive or inductive) reactive power with the bus.

The major control functions of a UPFC are active power and reactive power regulation on the series line and shunt bus voltage regulation. Although the UPFC has many possible operating modes, the automatic voltage control mode for shunt inverter and the power flow (P and Q) control mode for series inverter are the major operating modes [2]. In this mode, the shunt inverter reactive current is automatically regulated to maintain the transmission line voltage to a reference value, with a defined droop characteristic. The series converter regulates the real and reactive power on the compensated line to the reference Pref, Qref values within the operation boundary of the UPFC. The control scheme and the detailed simulation in this paper will focus on this operation mode for both steady state and dynamic conditions.

III. OPERATION OF SHUNT AND SERIES CONVERTERS

A.48-pulse voltage source converter

48-pulse voltage source converter consists of four 3-phase, 3-level inverters and four phase-shifting transformers introducing phase shift of +/- 7.5°. This transformer arrangement neutralizes all odd harmonics up to the 45th harmonic; except for the 23rd and 25th harmonics those two harmonics are minimized choosing an appropriate conduction angle for the three-level inverters.

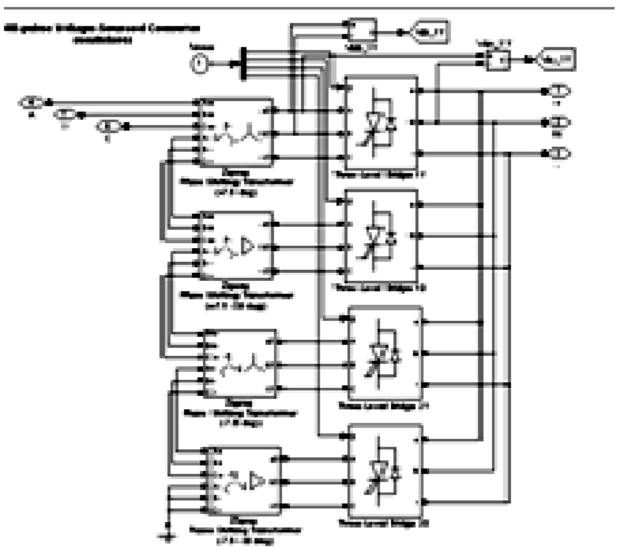


Fig. 2 The 48-pulse voltage source converter circuit and waveform construction for UPFC applications

Selecting GTO/Diodes pairs instead of Ideal Switches as power electronic devices. It would allow to specify forward voltage drops for GTOs and diodes and to observe currents flowing in GTOs and diodes by means of the Multimeter block.

The phase shifts produced by the secondary delta connections (-30 degrees) and by the primary zig-zag connections (+7.5 degrees for transformers 1Y and 1D, and -7.5 degrees for transformers 2Y and 2D) allows to neutralize harmonics up to 45th harmonic, as explained below:

The 30-degree phase-shift between the Y and D secondaries cancels harmonics 5+12n (5, 17, 29, 41, ...) and 7+12n (7, 19, 31, 43, ...). In addition, the 15-degree phase shift between the two groups of transformers (1Y and 1D leading by 7.5 degrees, 2Y and 2D lagging by +7.5 degrees) allows cancellation of harmonics 11+24n (11, 35, ...) and 13+24n (13, 37, ...). Considering that all 3n the harmonics are not transmitted by the Y and D secondaries, the first harmonic which are not cancelled by the transformers are 23rd, 25th, 47th and 49th. By choosing an appropriate conduction angle for the 3-level inverters (sigma = 180 - 7.5 = 172.5 degrees), the 23rd and 25th can be minimized. The first significant harmonics are therefore the 47th and 49th. This type of inverter generates an almost sinusoidal waveform consisting of 48-steps.

Fig. 2 shows the 48-pulse voltage source converter(VSC) topology and the output voltage waveform construction for shunt and series converter in UPFC. The VSC consists of four 3-level NPC converters (Inv1-Inv4) and four phase-shifting transformers(T1-T4).The four transformer primary windings(right side windings in Fig. 2) are connected in series and the converter switching pattern are phase shifted so that the four voltage fundamental components sum in phase on the primary side and generate a 48-pulse output voltage waveform.

The phase shift produced by the secondary delta connections of transformers T2 and T4 is -30 degrees, the phase shifts produced by the primary connections is +7.5 degrees for transformers T1 and T2, and -7.5 degrees for transformers T3 and T4.Therefore,the phase shift produced by the transformer T1,T2,T3 and T4 are +7.5, -22.5, -7.5,-37.5 degrees respectively. This allows the 48-pulse converter to neutralize harmonics up to 45^{th} harmonic [9,10]. The voltage waveform for each VSC output and the waveform construction(summation) on the transformer primary side is shown in Fig. 2. Each VSC is operated at fundamental frequency to reduce the switching loss ,and therefore achieves high efficiency.

Fig3. Shows the 3-level NPC converter and Fig. 4 shows its switching pattern with angle control. The output phase voltage could be three levels , +Vdc, 0, or –Vdc . As shown in Fig.4, there are two control variables in the switching pattern ,the phase shift angle(α) with respect to the line voltage and the duration of the +Vdc or –Vdc level (σ angle). Therefore , α angle determines the phase angle of the output voltage , while σ angle and the DC voltage control the magnitude of the fundamental component.

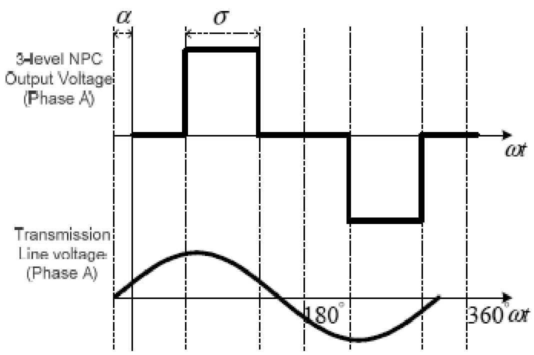
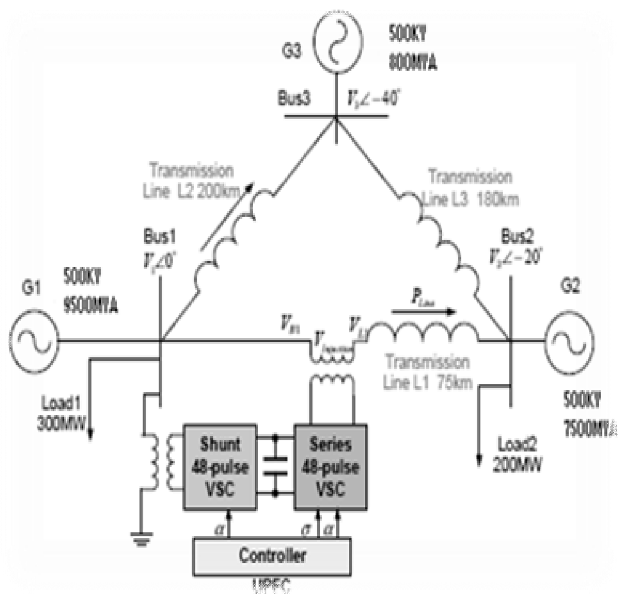


Fig. 3 Switching pattern of 3-level NPC converter(Top trace:3-level NPC converter Phase A output voltage; bottom trace: Transmission line bus voltage).

B. System Configuration

The 100 MVA UPFC is simulated in a 500-kV three-bus system and the system parameters are shown in Fig.5. The UPFC consists of a shunt and a series converter - both are implemented by 48-pulse series connected 3-level NPC converters.



The shunt transformer consists of four phase shifting transformers connected in series, each one is rated 25MVA, primary nominal voltage 125kV, secondary nominal voltage 3.75kV, winding resistance 0.05/30pu, winding inductance 0.05pu. Each phase shifting transformer in the series transformer has a primary nominal voltage 6.25kV, secondary nominal voltage 3.75kV. The DC filter capacitor C=3000µF.

The shunt converter is operated in voltage control mode with the control voltage reference Vref=1.0pu and a droop factor 0.03 pu/ 100MVA. The series converter is operated in power flow control mode, with real and reactive power references.

C .Shunt Converter Control

The UPFC shunt converter regulates the voltage on Bus 1 of the three-bus 500kV system as illustrated in Fig. 5. The shunt converter is "angle controlled" (angle α) to provide (or absorb) both real power and reactive power[11,12]. The voltage and current vector of shunt converter are shown in Fig.6.

The DC link voltage is varied higher or lower than the bus voltage so that the reactive power can be provided (capacitive) or absorbed (reactive) respectively. The phase angle α in steady state is determined by the real power transferred to series converter. The angle σ is fixed to minimize the harmonics.

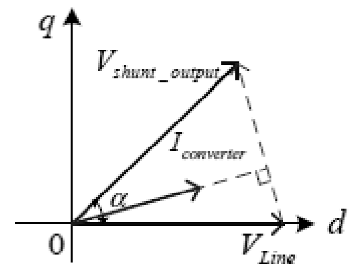


Fig.6 Voltage and current vector of shunt converter

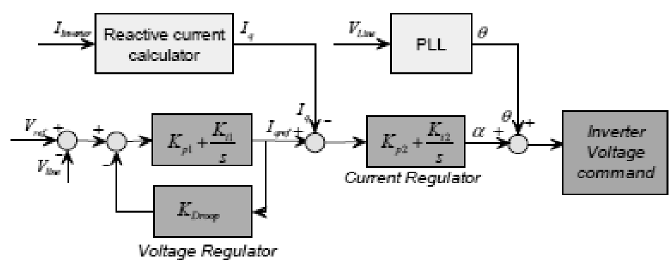


Fig. 7 Shunt converter angle controller diagram

In the control diagram, an inner current loop is used to regulate the shunt converter reactive current Iq and generate the phase shift angle α . The reference value of the Iqref reactive current control loop is generated by an outer voltage loop. The voltage regulator regulates the transmission line voltage with a defined droop characteristic.

D. Series Converter Control

The series converter is connected in series with line L1 through series insertion transformer as shown in Fig.5. The injection voltage can be any angle with respect to the line current but the magnitude is limited to 5% of the nominal line voltage.

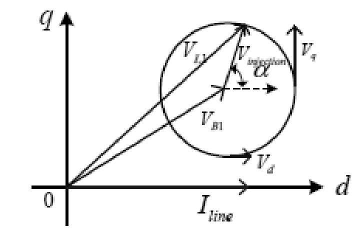


Fig.8 Voltage and current vector of series converter

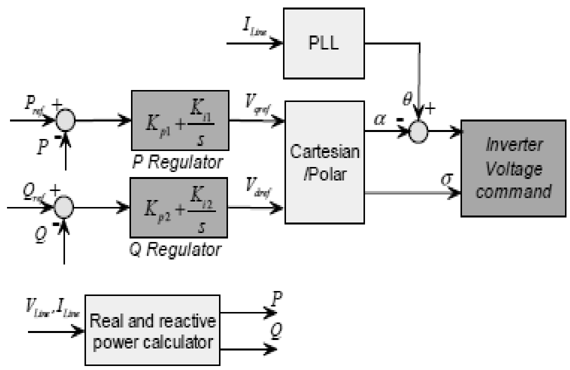


Fig.9 Series converter controller diagram

The series converter controls angle α to change the angle of the injected voltage relative to the line current. As the DC link voltage is determined by the shunt converter, the series converter controls the injected voltage magnitude by changing angle σ.

The injected voltage has two perpendicular components, Vd and Vq. Vd is the voltage component aligned with the line current and Vq is the voltage perpendicular with the line current. The voltage and current vector of the series converter is shown in Fig. 8. Vd and Vq determine the voltage injection magnitude and angle, and thus regulate the real and reactive power flow in the line.

Fig. 9 is the angle controller designed for the 48-pulse series converter. The series controller regulates the real power P and reactive power Q according to system reference command Pref and Qref. The Vq and Vd references are generated by P and Q regulator respectively, then the magnitude "m" and "angle α " of the output voltage are obtained by Cartesian-to-polar transform accordingly. The magnitude of injected voltage is varied by changing angle σ of the series converter. The real power and reactive power are thus regulated by voltage injection of the series converter. The proposed controller is implemented in Matlab/Simulink and the performance is evaluated by simulation results.

IV MATHMATICAL MODELLING

UPFC comprises a number of static synchronous compensators; SSSC and STATCOM in a transmission line; the compensating converters are connected together via a common DC link. The STATCOM help to supply or absorb real and reactive power for injection controllable voltage in series at two sides of a transmission line.

The 48 PULSE UPFC developed model in this section is based on the *d-q* orthogonal co-ordinates, the steady-state equations between the shunt and series inverters were strictly applied to the model, thus;

$$p_{sh} = p_{se} = p_{se1} + p_{se2} \quad — 1$$

$$p_{sh} = v_{busd}\, i_{shd} + v_{busq}\, i_{shq} \quad — 2$$

$$p_{se1} = v_{inj1d}\, i_{se1q} + v_{inj1q}\, i_{se1d} \quad — 3$$

$$p_{se2} = v_{inj2d}\, i_{se2q} + v_{inj2q}\, i_{se2d} \quad — 4$$

$$Q_{sh} = v_{busd}\, i_{shq} - v_{busq}\, i_{shd} \quad — 5$$

We can neglect the effect of resistances in the transmission line, thus we have

$$z_1 = jx_1, \; z_2 = jx_2$$

$$v_{bus} + v_{inj1} = v_1 + j\, x_1 i_{se1} = v_{seff1} \quad — 6$$

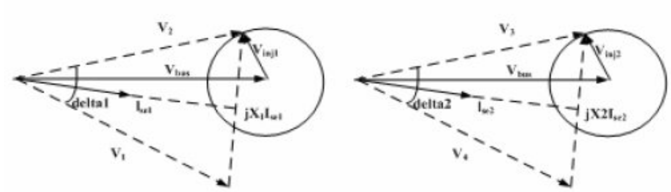
$$v_{bus} + v_{inj2} = v_4 + j\, x_2 i_{se2} = v_{seff2} \quad — 7$$

$$p_1 = \frac{v_{seff1} v_1 \sin \delta_1}{x_1} \quad — 8$$

$$Q_1 = \frac{v_{seff1}(v_{seff1} - v_1) \cos \delta_1}{x_1} \quad — 9$$

$$p_2 = \frac{v_{seff2} v_4 \sin \delta_2}{x_2} \quad — 10$$

$$Q_2 = \frac{v_{seff2}(v_{seff2} - v_4) \cos \delta_2}{x_2} \quad — 11$$



Phasor diagrams of voltage and current of UPFC

V. UPFC SIMULATION

To verify the proposed controller, the UPFC with series connected transformer based 48-pulse converter is simulated in Matlab/Simulink. The shunt converter is operated in voltage control mode and the series converter is operated in power flow control mode.

The real power and reactive power references of transmission line L1 are shown in Fig. 10 and Fig.11. The reference real power Pref changes from 0.9pu at 0.1s to 1pu at .15s. Similarly, the reference reactive power Qref changes from 0.04 at 0.05s to 0.06pu at 0.05s, and changes back from 0.06pu at 0.05pu to 0.1pu at 0.13s.

The measured power follows the references, which illustrates the independent control of real power and reactive power by the UPFC.

Fig. 12 also shows shunt converter angle α and Fig.13, Fig.14 series converter angle α and σ . The shunt converter angle α is shifted to vary the DC bus voltage. The series converter angle α and σ are also varied to regulate the power flow.

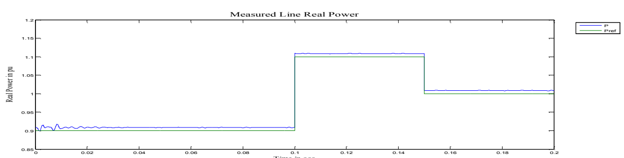


Fig.10 M easured and reference real power

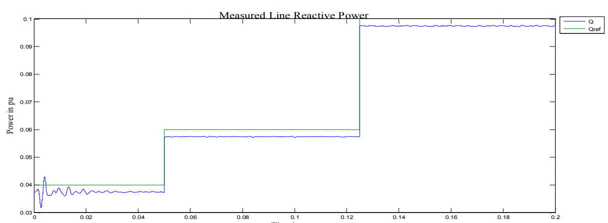


Fig.11 Measured and reference reactive power

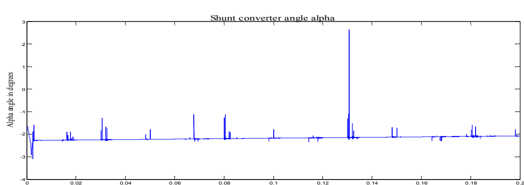


Fig12. Shunt converter angle

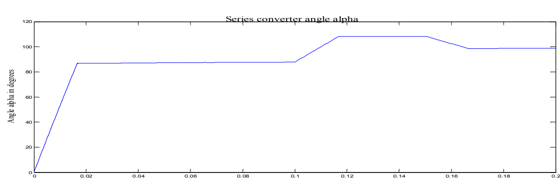


Fig.13 Series converter angle alpha

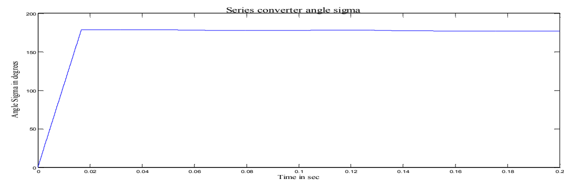


Fig.14 Series converter angle sigma

V. CONCLUSIONS

In this paper, the control and operation of series and shunt converters with 48-pulse series connected 3-level NPC converter for UPFC application are investigated. A new angle controller for 48-pulse series converter is proposed to control the series injection voltage, and therefore the real and reactive power flow on the compensated line. The practical UPFC real and reactive power operation boundary in a 3-bus system is investigated; this provides a benchmark to set the system P and

Q references. The simulation of UPFC connected to the 500-kV grid verifies the proposed controller and the independent real power and reactive power control of UPFC with series connected transformer based 48-pulse converter.

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