High Power Neutral Point Clamped (NPC) Multilevel UPFC with DC Link Switch for Effective Control of Real & Reactive Power

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Abstract – High-voltage and power capability of multilevel converters better used for unified power-flow controller (UPFC) applications. The three-level neutral-point-clamped (NPC) converter allows back-to-back connection as the UPFC shunt and series converters than other multilevel topologies. In place of the pulse width-modulated (PWM) multilevel control schemes, constant dc-link voltage and balanced voltages in the NPC multilevel dc capacitors is necessary for UPFCs. The proposed work provides three main contributions to increase the performance of the system of multilevel UPFCs as this can be operated in STATCOM, SSSC and exactly in the UPFC mode with the double balancing of dc capacitor voltages under line faults, overall enhancing the UPFC ride-through capability. NPC series and shunt converters keep the dc-link voltage steady. Transients are the causes of fault in power system, Power System Stabilizer (PSS) and Automatic Voltage Regulator (AVR) are used to stabilize the response. The voltage regulator and current controller plays important role to generate control pulses for VSC. A MATLAB simulation has been carried out to demonstrate the performance of the proposed model for UPFC in achieving transient stability with real and reactive power control.

Keywords – Power System Stabilizer (PSS), unified power-flow controller (UPFC), neutral-point-clamped (NPC), Voltage source converters (VSC), The Flexible Alternating Current Transmission System (FACTS), Automatic Voltage Regulator (AVR), proportional integral (PI)

I. INTRODUCTION

The UPFC (Unified Alternating Current Transmission System) are becoming effective in suppressing power system oscillations, improving system damping and control the active and reactive power. This proposed work investigating the performance of UPFC with respect to the ideal and actual response of the system to achieve stability and it is seen and verified by the results. The effectiveness of the proposed dc link switch based UPFC in suppressing power system oscillation is investigated by analyzing line injection voltage, real and reactive power, dc link voltage and current. A proportional integral (PI) controller has been employed for the UPFC to control the voltage source converters (VSC) current, voltage and phase of the transmission lines. In power networks highly use of power electronic devices because of their multiple functions: compensation, protection and interface for generators.

II. MODEL BASED ON FACTS DEVICES

According to definition of IEEE, “The Flexible Alternating Current Transmission System (FACTS) is new technology based on power electronic devices which offers an prospect to increase controllability, stability and power transfer capability of Alternating Current Transmission Systems” [7].
To enhance the growth of industrial area, it is required to provide a stable, secure, controlled and economic quality in highly complex system. To achieve for better quality of power, it is compulsory to increase the transmitted by installing new transmission lines or by improving previous lines by adding new controlling devices. Installation a new transmission lines is not possible because of few reason like economic condition, cost and time taken. Therefore power engineers concentrated the research process to installed control devices in existing transmission system.

First Generation of FACTS Controllers:
- Static Var Compensator (SVC) and
- Thyristor Controlled Series Compensator (TCSC)

Second Generation of FACTS Controllers:
- Static Synchronous Series Compensator (SSSC) and
- Static Synchronous Compensator (STATCOM)

Third Generation of FACTS Controllers:
- Unified Power Flow Controller (UPFC)
- Interline Power Flow Controller (IPFC) and

Fourth Generation of FACTS Controllers:
- Generalized Power Flow Controller (GUPFC)

Unified Power Flow Controller (UPFC):
The UPFC is a combination of series compensator (SSSC) and shunt compensator (STATCOM) link with common DC capacitor. It has ability to simultaneously control all the parameters of transmission systems, like voltage, impedance and phase angle.

The UPFC has ability to solve all problems occurring in the power flow control and transmission line compensation with the help of solid-state controllers, which provide flexibility which is not obtained in thyristor-controlled controllers.

Control Modelling:
In an open loop, the phase \( \Theta \) and magnitude \( M \) of modulating signal is used for calculation the Fourier coefficients of switching function which is constant and known. In the close loop these two parameters are used to control state variables of magnitudes converter, in ac current.

By calculating the phase and magnitude of the modulating signal it control the input systems. By replacing the state variable converter of reference values, the fundamental frequency and the fundamental switch function is obtained in Equation (13). The modulating signal parameters are obtained by fundamental of switching function. Taken into a account by knowing \( M \) and \( \Theta \) the real switching function obtained.

The passive elements are considered as equal in three phases:

\[
\begin{align*}
L_1 &= L_2 = L_3 = L_i \\
R_i &= R_3 = R_1 = R_i
\end{align*}
\]

Above equations only one phase converter is considered. Then, Eq is written as:

\[
\begin{align*}
u_i &= i_x + j \Omega \psi \\
V &= V_d + j V_q \\
u &= u_d + j \Omega u_q
\end{align*}
\]

Equations transformed in dq structure:

\[
\begin{align*}
L \frac{di_d}{dt} &= \omega L i_q - R_i i_d + \frac{1}{2} u_d V_d \\
L_i \frac{di_q}{dt} &= -\omega L i_d - R_i i_q + \frac{1}{2} u_q V_d \\
C \frac{dV_d}{dt} &= \frac{3}{2} (u_d i_d + u_q i_q) - \frac{V_d}{R}
\end{align*}
\]

In the dq structure the magnitudes of the state variables are constant, so that derivative is equal to zero:

\[
\begin{align*}
\frac{dV_d}{dt} &= 0 \\
\frac{dV_q}{dt} &= 0 \\
\frac{dV_d}{dt} &= 0
\end{align*}
\]

By considering the ac current equal to reference value (PI controllers are ideal), then \( d \) and \( q \) components of switching functions is:

\[
\begin{align*}
u_d &= \frac{1}{2} \sqrt{2} \left( R_{1 \omega} a_d i_{\omega d} - R_{1 \omega} i_{\omega d} - V \right) + i_{\omega d} \left( -\alpha_d i_{\omega d} - R_{1 \omega} i_{\omega d} \right) \\
u_q &= \frac{1}{2} \sqrt{2} \left( R_{1 \omega} a_d i_{\omega q} - R_{1 \omega} i_{\omega q} - V \right) \\
u_d &= \frac{1}{2} \sqrt{2} \left( -\alpha_d i_{\omega q} - R_{1 \omega} i_{\omega q} \right)
\end{align*}
\]

The values of \( u_d \) and \( u_q \), the fundamental magnitude and phase of switching function are calculated:

\[
\begin{align*}
M &= \sqrt{u_d^2 + u_q^2} \\
\theta &= -\arctan \left( \frac{u_q}{u_d} \right)
\end{align*}
\]

III. Equivalent Circuit Operation of UPFC

In Fig. 2, the two-voltage source converters is changes as two ideal voltage sources, one is connected in series and another is shunt between the two buses. The output of
The active and reactive power equation is written as,

\[ P \equiv V^2 \sin \theta \text{ and } Q \equiv V^2 \cos \theta \]

The active and reactive power from the shunt converter to the AC system is obtained by exchanging state combinations \( \Gamma \) as follows:

\[ P = V^2 \sin \theta \text{ and } Q = V^2 \cos \theta \]

where \( V \) is the voltage magnitude and \( \theta \) is the angle of converter output voltage.

The supplied active power in shunt converter \( P_s \) equals to demanded active power in series converter \( P_s \).

\[ P_s + P_f = 0 \]

However, to suppose the coupling transformers have zero resistance then active power at bus K equating to bus M that is,

\[ P_s + P_f = P_s + P_f = 0 \]

The linearized equation of UPFC and combined with AC transmission system.

1. The shunt converter terminal at voltage magnitude.
2. Active power flow from bus m to bus k.
3. In bus M injected reactive power and this bus to be PQ bus.

**IV. WORKING & SIMULATION**

**NPC Converter Model:**

In every three-level NPC converter, the three-phase output voltages \( V_p \) are connected to the AC system expressed by their Thevenin proportional (impedance R, L and open-circuit electromotive power \( U_{dc} \)). A non-exclusive variable \( p \in \{c, v\} \) is utilized to speak to either the series converter variables \( p=\text{c} \) then again the shunt converter \( p=\text{v} \). Both series and shunt converters share the DC-link voltage \( V_d \) and the voltages \( V_{c1}, V_{c2}, V_{c3} \) and \( V_{c4} \) of the four capacitor banks \( C_1, C_2, C_3 \) and \( C_4 \), respectively. Contingent upon the current \( i_0 \) sign, the converter works in the inverter mode \((i_0>0, \text{ DC/AC converter})\) or in the rectifier mode \((i_0<0, \text{ AC/DC converter})\).

To get a dynamic model of the NPC converters, semiconductors are viewed as perfect switches. The state variables are the AC current \( i \) for the series converter, the AC current \( i_v \) of the shunt converter, and the dc voltages \( V_{c1}, V_{c2}, V_{c3} \) and \( V_{c4} \).

The currents and voltages are identified with the variables \( y_{pk} \). Applying Kirchhoff's laws to the instantaneous voltages and current, that dependence is communicated by state combinations \( \Gamma_{1kp} \).

\[ \Gamma_{1kp} = \frac{y_{pk}(1+y_{pk})}{2} \]

\[ \Gamma_{1kp} = \frac{y_{pk}(1+y_{pk})}{2} \]

For every three-level converter \( p \in \{c, v\} \), then \( I_{pk} = -(2\delta_{pk} - 1) \Gamma_{1kp} \) and \( I_{pk} = -(2\delta_{pk} - 1) \Gamma_{1kp} \), where the Kronecker delta \( \delta \) is \( \delta_{pk} \) if \( p=r, c \), or \( \delta_{pk} = 0 \) if \( p \neq c \). The leg-to-ground point voltage \( u_{np} \) is given as \( u_{np} = \Gamma_{1kp}V_{c1} + \Gamma_{2kp}V_{c2} + \Gamma_{3kp}V_{c3} + \delta_{pk} \), and the dc rail current are \( i_{pk} = \sum_{k=1}^{3} I_{pk} \) and \( i_{pk}' = \sum_{k=1}^{3} I_{pk}' \). Further, the line-to-ground AC voltages \( V_p \) in the \( \alpha, \beta \) plane \( V_{a}, V_{b}, V_{c} \) can be acquired utilizing the Clarke–Concordia matrix to change the \( \Gamma_{1kp}(\alpha \in \{1, 2, 3\}, p \in \{c, v\}) \) variables of (15) into the \( \alpha, \beta \) plane, resulting in \( \Gamma_{1kp}, \Gamma_{1kp}', \Gamma_{2kp}, \Gamma_{2kp}' \) and \( \Gamma_{2kp}' \). For brevity, they are signified in (16) as \( \Gamma_{1kp}, \Gamma_{1kp}', \Gamma_{2kp}', \) and \( \alpha \beta \in \{1, 2, 3\} \).

\[ \frac{\Gamma_{1kp}}{\sqrt{2}} \]

\[ \frac{\Gamma_{1kp}'}{\sqrt{2}} \]

\[ \frac{\Gamma_{2kp}'}{\sqrt{2}} \]

\[ \frac{\Gamma_{2kp}'}{\sqrt{2}} \]
Thusly, the series converter line-to-ground voltages $V_{c}$ in the $\alpha$, $\beta$ plane $V_{c} = [V_{c\alpha}, V_{c\beta}]^T$ are written as in (17), where the subscript “c” means the series converter variables.

For the shunt converter, a comparative mathematical statement could be composed:

$$
\begin{bmatrix}
V_{cu} \\
V_{cg}
\end{bmatrix} =
\begin{bmatrix}
\|c_{i}\| \\
\|c_{g}\|
\end{bmatrix}
$$

Expecting a suitable control activity to adjust the capacitor voltages $V_{c\alpha}$ and $V_{c\beta}$, the series converter line-to-neutral voltages $V_{c\alpha,\beta}$ can be communicated as $V_{c\alpha,\beta} = \gamma \approx V_{c}/2$, so that $V_{c\beta} = V_{c\alpha}/2$, with $\gamma \approx c\sqrt{2}/2$, the resulting changes in $V_{c\alpha,\beta}$ can be communicated as $V_{c\alpha,\beta} = \gamma \approx V_{c}/2$.

Considering the capacitor $V_{c\alpha}$ and $V_{c\beta}$ voltages, and the shunt converter AC phase currents $i_{c}$ in the shunt transformer with sifting inductors (impedance $R_{i}$, $L_{c}$).

**V. RESULTS AND DISCUSSION**

On the basis of methodology and mathematical modelling proposed in earlier discussions, the values of various circuit parameters were calculated and are tabulated as below-

**Design Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DC-link voltage</td>
<td>12 kV</td>
</tr>
<tr>
<td>Programmable voltage source</td>
<td>500 kV</td>
</tr>
<tr>
<td>STATCOM (Qref) [T1, T2, Q1, Q2]</td>
<td>0.3, 0.5, +0.8, -0.8</td>
</tr>
<tr>
<td>STATCOM Vref (pu) [Initial Final Stop Time]</td>
<td>1, 1.005, 0.3*100</td>
</tr>
<tr>
<td>SSSC Vinj (pu) [Initial Final Stop Time]</td>
<td>0.0, 0.08, 0.3</td>
</tr>
<tr>
<td>UPFC Pref (pu) [Initial Final Stop Time]</td>
<td>+8.7, +10, 0.25</td>
</tr>
<tr>
<td>UPFC Qref (pu) [Initial Final Stop Time]</td>
<td>-0.6, 0.7, 0.5</td>
</tr>
<tr>
<td>Shunt STATCOM (Vref in pu)</td>
<td>1.00</td>
</tr>
<tr>
<td>Shunt STATCOM Drop (pu/100 MVA)</td>
<td>0.01</td>
</tr>
<tr>
<td>Shunt STATCOM [Kp Ki]</td>
<td>[12, 3000]</td>
</tr>
<tr>
<td>Shunt STATCOM</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Series UPFC Pref, Qref (pu/100 MVA)</td>
<td>[8.7, -0.6]</td>
</tr>
<tr>
<td>Series UPFC voltage injection</td>
<td>0.07</td>
</tr>
<tr>
<td>Series UPFC [Kp Ki]</td>
<td>[0.25, 1.5*4]</td>
</tr>
</tbody>
</table>

**Characteristics of P-Q with 0.1 pu injected voltage**

The characteristics of $P$ and $Q$ with 0.1 pu injected voltage shows the UPFC controllable region in fig. 7.1. Having four sets of surface region i.e.,

1. Angle $V_{m} = 0$ deg, $P = 870$ MW and $Q = 60$ Mvar
2. Angle $V_{m} = 90$ deg, $P = 1225$ MW and $Q = 10$ Mvar
3. Angle $V_{m} = 180$ deg, $P = 819$ MW and $Q = 370$ Mvar
4. Angle $V_{m} = 270$ deg, $P = 553$ MW and $Q = 66$ Mvar

**UPFC Response**

The steady state of active power is reached ($P=+8.7$ pu) behind the transient period approx. 0.15 sec. After new settings of $P$ ($P=+10$ pu) is ramped to by changing the reference value to $0.25$ second. In fig 7.12.

The reference value of reactive power is changed at time $t=0.5$ sec, to 0.7 pu and the reactive power occurred a new value after 0.15 sec. in fig 7.13.

**Fig. 4. UPFC responses active power changing**

The P (L1, L2, L3) is the active power shown in fig. 7.14. And it is observe that resulting changes in active power flow in the 3 transmission lines. The blue line shows the UPFC response.

**Fig. 6. Active power response in 3 transmission line**

A. The Q (L1, L2, L3) is the reactive power shown in fig. 7.15. And it is observe that resulting changes in reactive power flow in the 3 transmission lines. The blue line shows the UPFC response.
The proposed high power multilevel UPFC control strategy includes dc-link voltage control gains with low sensitivity to dc-link current and the balancing of the dc-link capacitor voltages using both multilevel converters. The dc-link capacitor voltages are balanced using both series and shunt multilevel converters in spite of only one of the multilevel converters. The main improvement is to reduce the harmonics by 16% of the line voltage and stabilization of the system. This shows the effectiveness of the proposed work to operate in three different modes as per the requirement compared to the works which have been already implemented.

This is useful to in the high power transmission lines for the stabilization of the system and also to maintain the line voltage as per the demand with good power quality aspects. Here as the dc-link capacitor is introduced between two converters known as series and shunt converters maintain the level of it.

### References


VI. CONCLUSION AND FUTURE WORK

The stability of power system using FACTS devices like UPFC is compared and discussed, with the major disturbance the dynamics of the system is compared with the presence of STATCOM & UPFC in the system. Improvement in stability is compared with the reference work with has been already done, by using the STATCOM. The simulation results show that considerable improvement in the system performance with the use of UPFC as system stabilization and the harmonics in the line voltage. The proposed high power multilevel UPFC control strategy includes dc-link voltage control gains with low sensitivity to dc-link current and the balancing of the dc-link capacitor voltages using both multilevel converters. The dc-link


