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Proceedings Paper:

Huang, H, Zhang, L and Chong, BVP (2018) Control of A Modular Multilevel Cascaded Converter based Unified Power Flow Controller. In: Proceeding of IECON 2018. 44th Annual Conference of the IEEE Industrial Electronics Society, 21-23 Oct 2018, Washington, D.C., USA. IEEE , pp. 3926-3931. ISBN 978-1-5090-6684-1

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Control of A Modular Multilevel Cascaded Converter based Unified Power Flow Controller

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Abstract — This paper presents a novel configuration of unified power flow controller (UPFC) using a three-phase modular multilevel cascaded converter (MMCC) shunt connected on one end of the transmission line. This offers control flexibility, lower cost and losses compared to the conventional UPFC. The control scheme combines the power flow regulation at the series converter side and voltage control at the shunt MMCC part. An overall DC capacitor voltage balancing scheme is implemented to ensure all floating capacitors of shunt MMCC and series converter voltages can be maintained at their nominal values. Simulation studies of this MMCC-UPFC for a simple two voltage sourced power network are presented and results verifies its good performance under varying real and reactive power flow conditions.

Keywords — *Modular multilevel cascaded converter; Unified power flow controller; Flying capacitor converter*

I. INTRODUCTION

The development of power electronics in recent years has led to the applications of advanced power semiconductor switching devices, such as Flexible AC Transmission Systems (FACTS) with sophisticated configurations and control techniques for the network power flow control. They offer power quality improvement, higher flexibility and fault tolerance to the power system operation. Though at higher costs, they can give reduced operation and transmission cost, increased power transfer capability and reliability.

The Unified Power Flow Controller (UPFC) is the most versatile device among the Flexible AC Transmission Systems (FACTS) [1]. It is able to realise simultaneous voltage regulation, line impedance compensation and phase angle adjustment, hence achieving flexible independent control of real and reactive power flow along the compensated transmission lines and increased power transfer stability margins [2, 3].

The conventional UPFC configuration is shown in Fig. 1, which is a combination of two voltage source converters (VSCs), connecting ‘back-to-back’ through a common DC-link. The VSC1 is connected in parallel with the transmission line through a voltage step-up transformer. It can provide bidirectional real power exchange between the two VSCs, and

maintain the DC-link capacitor voltage balanced. The VSC2 is connected in series with the transmission line through a series transformer. This injects a 4-quadrant controllable AC voltage V_{c1} to the primary side of the transformer so that it can achieve real and reactive power flow control along the transmission line. As it can be seen, both the DC-link bus and interfacing transformers cannot be neglected as the former offers real power supplement for the VSC2 from VSC1, and the latter provides voltage matching and galvanic isolation between the device and transmission line. However, the requirement of a bulky transformer increases cost, losses and footprint [4] and also gives slower dynamic response. To eliminate the disadvantages several alternative UPFC topologies have been investigated [5-9], but they still have drawbacks such as requiring bulky transformers on both sides.

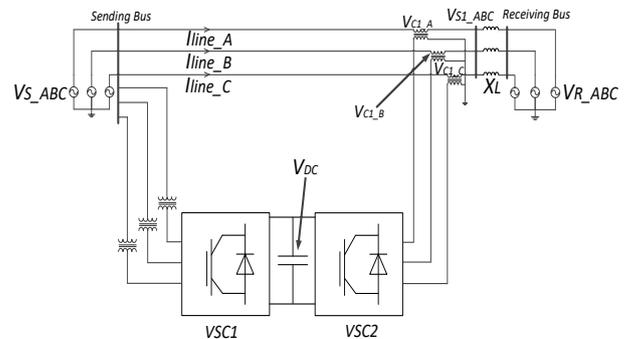


Fig. 1. Conventional UPFC circuit diagram

This paper proposes a novel configuration with its control schemes of UPFC based on modular multilevel cascaded converters [10-13]. The MMCC can reach to the required voltage levels without the high cost and bulky shunt interface transformer. Its other benefits are well-known including reduced converter switching frequency hence losses and cost. The structure of this paper is by giving the MMCC-UPFC configuration and its working principle with phasor diagram in section 1; its shunt MMCC and series converter control strategies and derivations are described in section 2. The simulation study and results discussions shown the effectiveness and controllability of the device are finally presented.

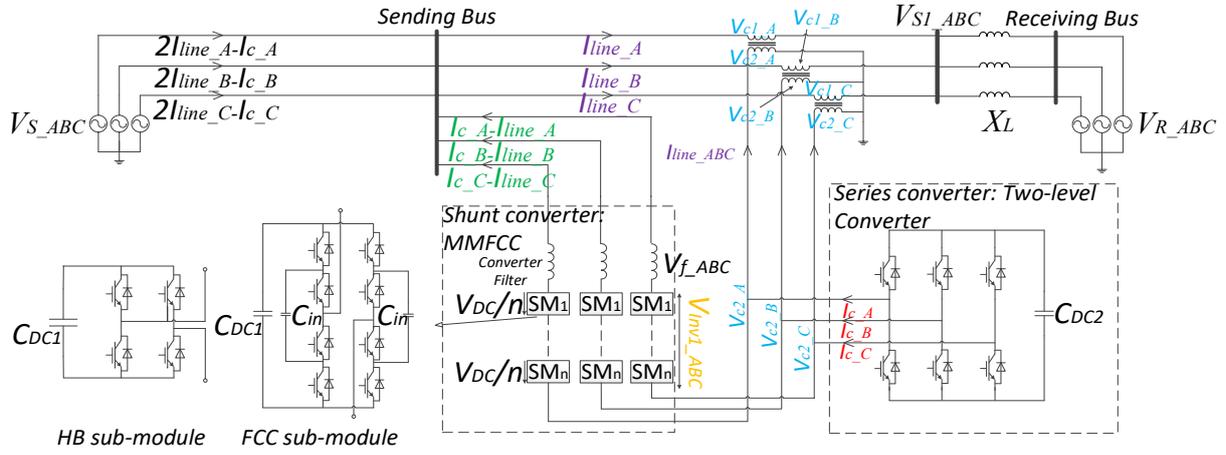


Fig. 2. 3-phase transmission system with novel MMCC-UPFC circuit diagram

II. SYSTEM CONFIGURATION AND OPERATING PRINCIPLE

A. Novel MMCC-UPFC circuit with 3-phase transmission system

The structure of the power system with an MMCC-based UPFC is shown in Fig. 2. There are V_{S_ABC} and V_{R_ABC} representing respectively the sending and receiving ends of a 3-phase network linked by a transmission line. The VSC2 is a three-phase 2-level voltage source inverter. Its 3 phases' AC sides are connected to a three-phase transformer whose primary side windings are connected in series with the transmission lines. An MMCC is shunt connected with the transmission line in Fig. 1 as VSC1. The submodules (SM) of MMCC can be formed by either full H-bridge (HB) or any other converter topologies, here the 3-level flying capacitor converters (FCC) are used. Hence each SM consists of eight transistors, three capacitors, one is SM DC capacitor C_{DC1} and the others are two flying capacitors C_{in} . Each can synthesis five voltage levels; $\pm V_{DC}$, $\pm 0.75V_{DC}$, $\pm 0.5V_{DC}$, $\pm 0.25V_{DC}$ and 0 Volt. The number of chained submodules may vary according to the transmission line voltage rating and the DC capacitor voltage per module. Having multiple submodules per phase, higher AC voltage magnitudes and lower switching frequencies hence also lower switching losses can be achieved simultaneously. Unlike the conventional UPFC, there is no DC-link shared between the two VSCs and they are linked instead on the AC side. The MMCC has the following features:

- Full modularity and flexibility and each submodule can be individually controlled and bypassed when fault occurs.
- Shunt connected to the transmission line through an inductor filter, thus no transformer at the shunt part is required.
- Not shared capacitors between shunt MMCC and the series VSC.

B. Operating principle

The equivalent circuit of the proposed MMCC-UPFC with its voltage and current phasor diagram is illustrated in Figs. 3 and 4. Assuming the series transformer is Y-Y connected and

a desired $V_{c2} \angle \delta$ is generated at the converter side. This will be converted to $V_{c1} \angle \delta$ of the same phase angle at the transmission line side. The current flowing out from the series converter is \vec{I}_c , which should be in quadrature with its voltage \vec{V}_{c2} and thus entirely reactive.

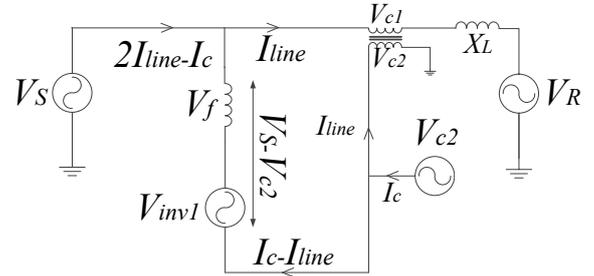


Fig. 3. MMCC-UPFC equivalent circuit

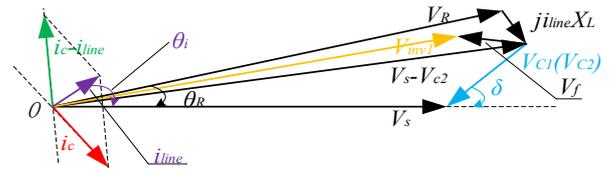


Fig. 4. UPFC voltage and current phasor diagram

Moreover, the shunt converter voltage is in between with the sending bus voltage and series converter voltage, thus can be derived as $(\vec{V}_s - \vec{V}_{c2})$ and the MMCC's voltage \vec{V}_{inv1} excluding inductor filter losses \vec{V}_f . The current generated by the MMCC is according to the series converter and transmission line current as $(\vec{I}_c - \vec{I}_{line})$, which is also perpendicular with its voltage \vec{V}_{inv1} and therefore entirely reactive.

The current flow through the MMCC plays an important role in controlling both shunt SMs and series converter DC capacitor voltages, as it controls the two converters' current in quadrature with their voltages. However, losses in the devices exist which consume real power, hence an additional control

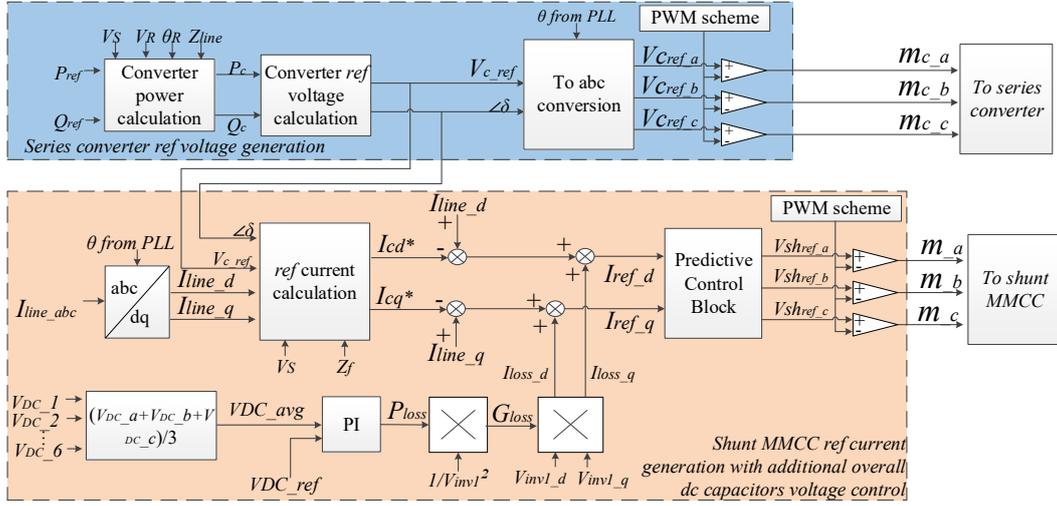


Fig. 5. MMCC-UPFC control block diagram

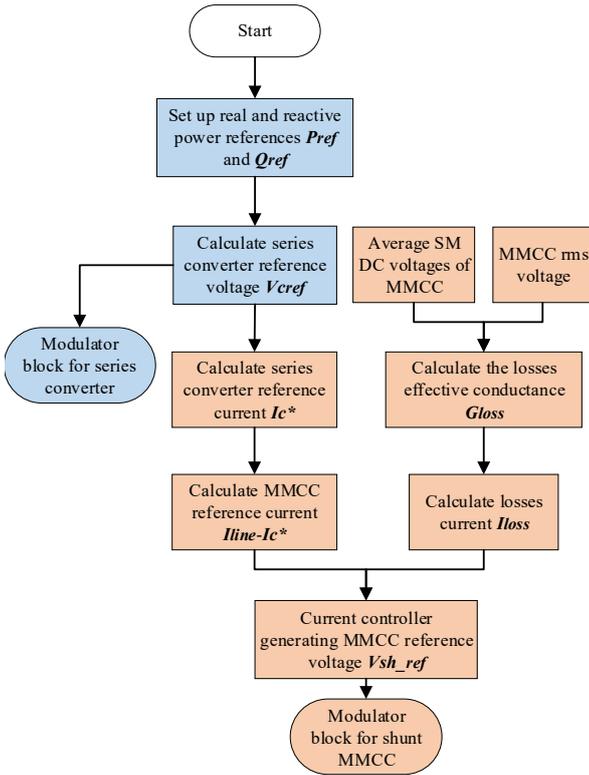


Fig. 6. Flowchart of MMCC-UPFC control schemes

to compensate this loss of real power is required for the MMCC. It is expected that it can generate exact current for the purpose of zero active power exchange between the two converters.

III. CONTROL STRATEGIES

The overall control strategies and corresponding implementation flowchart are illustrated in Figs. 5 and 6. The control is divided into two main parts:

- Control the series converter AC voltages in order to regulate the power flow from sending to the

receiving buses. This involves calculating the required V_{c_ref} according to the reference real and reactive power commands, which will be set as the reference voltage of the series converter.

- Regulate the current flow through the shunt MMCC for voltage regulation at the sending line whilst maintaining both SM and series converter DC capacitor voltages balanced. This requires calculating the $(\vec{I}_c - \vec{I}_{line} + \vec{I}_{loss})$ via feedback control of the overall DC capacitor voltage. Thus the converters' voltage vector is perpendicular to their currents and thus no active power exchange between the two converters.

A. Series converter reference voltage generation

The control of transmission line power flow depends on the voltage \vec{V}_{c2} generated by the series converter and its converting to \vec{V}_{c1} . Note that all the calculations are taken the sending bus voltage as the reference. Therefore, the equation for power flow under the UPFC control can be derived as

$$P_{ref} + jQ_{ref} = \vec{V}_R \vec{I}_{line}^* = \vec{V}_R \left(\frac{\vec{V}_S - \vec{V}_R - \vec{V}_{c1}}{jX_L} \right)^* = \left[\frac{V_R V_{c1} \sin(\theta_R - \delta) - V_S V_R \sin \theta_R}{X_L} \right] + j \left[\frac{V_S V_R \cos \theta_R - V_R^2 - V_R V_{c1} \cos(\theta_R - \delta)}{X_L} \right] \quad (1)$$

Initially, without the UPFC control, the power flow of the transmission line under the same condition is

$$P_0 + jQ_0 = \frac{-V_S V_R \sin \theta_R}{X_L} + j \frac{V_S V_R \cos \theta_R - V_R^2}{X_L} \quad (2)$$

Therefore, the 'injected' real and reactive power by the UPFC device can be calculated as:

$$\begin{cases} P_C = P_{ref} - P_0 = \frac{V_R V_{c1} \sin(\theta_R - \delta)}{X_L} \\ Q_C = Q_{ref} - Q_0 = \frac{-V_R V_{c1} \cos(\theta_R - \delta)}{X_L} \end{cases} \quad (3)$$

From the above equation set, the required magnitude V_{c1} and angle δ can be illustrated as:

$$V_{c1} = \frac{X_L}{V_R} \sqrt{P_C^2 + Q_C^2}$$

$$= \frac{X_L}{V_R} \sqrt{\left(P_{ref} + \frac{V_S V_R \sin \theta_R}{X_L}\right)^2 + \left(Q_{ref} - \frac{V_S V_R \cos \theta_R - V_R^2}{X_L}\right)^2} \quad (4)$$

$$\delta = \theta_R - \arctan\left(\frac{P_C}{Q_C}\right) = \theta_R - \arctan\left(\frac{P_{ref} + \frac{V_S V_R \sin \theta_R}{X_L}}{Q_{ref} - \frac{V_S V_R \cos \theta_R - V_R^2}{X_L}}\right) \quad (5)$$

The series converter reference voltage $\overrightarrow{V_{c,ref}}$ thus can be derived by the above magnitude V_{c1} and its angle δ , $\overrightarrow{V_{c,ref}} = V_{c1} \angle \delta$.

B. Shunt MMCC reference current generation

According to the previous sub-section, the series converter generated voltage is $\overrightarrow{V_{c2}} \angle \delta$, $\angle \overrightarrow{I_c} = \delta - 90^\circ$. $\overrightarrow{I_c}$ magnitude can be derived as follow:

The active power flowing into the shunt MMCC can be written as:

$$P_1 = 0 = (\overrightarrow{V_s} - \overrightarrow{V_{c2}} - \overrightarrow{V_f}) \times (\overrightarrow{I_c} - \overrightarrow{I_{line}})$$

$$= (\overrightarrow{V_s} - \overrightarrow{V_{c2}} - Z_f(\overrightarrow{I_c} - \overrightarrow{I_{line}})) \times (\overrightarrow{I_c} - \overrightarrow{I_{line}})$$

$$= Z_f I_c^2 - V_S I_c \sin \delta + V_S I_{line} \cos \theta_i$$

$$+ Z_f I_{line}^2 - V_{c2} I_{line} \cos(\delta - \theta_i) \quad (6)$$

Thus, I_c can be regarded as the only unknown of the above quadratic equation.

$$\Delta = (V_S \sin \delta)^2 - 4Z_f(V_S I_{line} \cos \theta_i + Z_f I_{line}^2 - V_{c2} I_{line} \cos(\delta - \theta_i)) \quad (7)$$

The equation is effective only when $\Delta \geq 0$, otherwise there is no solution of I_c , which means the UPFC cannot work under that condition.

$$I_c = \frac{V_S \sin \delta \pm \sqrt{\Delta}}{2Z_f} \quad (8)$$

Therefore, $\overrightarrow{I_c} = \frac{V_S \sin \delta \pm \sqrt{\Delta}}{2Z_f} \angle \delta - 90^\circ$ and the shunt MMCC generating current ($\overrightarrow{I_c} - \overrightarrow{I_{line}}$) can also be decided.

However, in reality the converter losses which draws amount of real power cannot be neglected, hence its voltage and current cannot be quadrature and always have a phase shift from 90° , consequently the DC capacitors of the MMCC and series converter may drift away from their nominal values. An additional overall dc capacitors voltage control thus is added into the control scheme to compensate this part of real power losses.

To compensate the losses it is necessary to calculate the total conductance G_{loss} which draws real power, this is achieved by using the average of total SM DC capacitor

voltages comparing with the reference value and regulating to the real power losses P_{loss} through a PI controller, and then being divided by the square of MMCC voltage rms value. Then, the product of G_{loss} and the voltage is the current I_{loss} required for compensating the losses and can be added into the ($\overrightarrow{I_c} - \overrightarrow{I_{line}}$) to generate corresponding reference current I_{ref} . Fig. 6 shows the comparative results without and with the additional DC capacitors voltage control loop, which can be found that the DC capacitors voltage can be maintained at their nominal value when the I_{loss} added in while it will drift away when the current is zero.

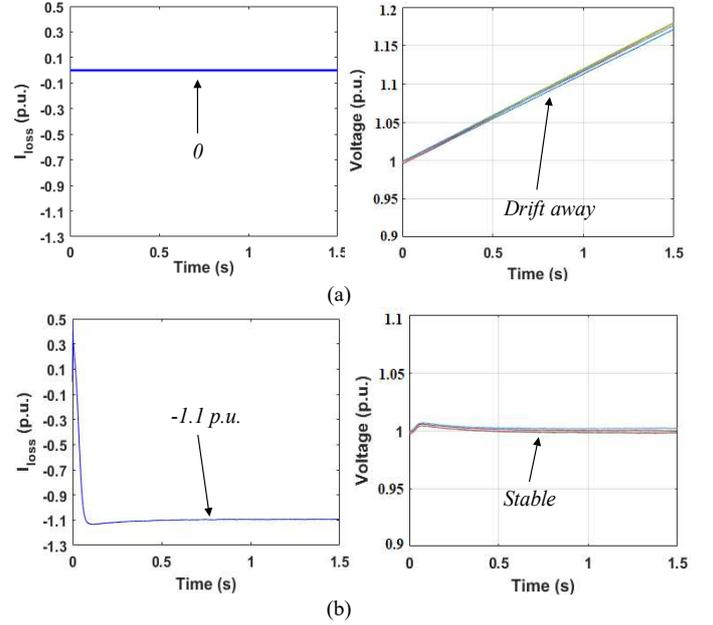


Fig. 7. The I_{loss} current (left) and MMCC DC capacitor voltages (right) (a) without and (b) with overall DC capacitor voltage control

After the shunt MMCC reference current decided, a predictive controller is adopted to generate the reference voltage V_{inv1}^* , which is based on the space vector equation given by

$$\overrightarrow{V_s} - \overrightarrow{V_{inv1}} = L_f \frac{d\vec{i}}{dt} + R_f \vec{i} \quad (9)$$

When implemented in a real digital system, a small sampling period (T_s) is chosen and $\frac{d\vec{i}}{dt}$ is expressed by

$$\frac{d\vec{i}}{dt} = \frac{\Delta \vec{i}}{T_s} = \frac{\vec{i}(k+1) - \vec{i}(k)}{T_s} \quad (10)$$

where T_s is defined as the time between k^{th} and $(k+1)^{\text{th}}$ samples. Since the next sampling period current $\vec{i}(k+1)$ cannot be known in advance, so it is replaced by the current reference value $\overrightarrow{i_{ref}}(k)$. After substituting (10) into (9) and doing re-arrangement, the required reference voltage at the next sampling period can be derived as (11).

$$\overrightarrow{V_{inv1}}(k) = \overrightarrow{V_s}(k) - \left[\frac{L_f}{T_s}\right] \overrightarrow{i_{ref}}(k) + \left[\frac{L_f}{T_s} - R_f\right] \vec{i}(k) \quad (11)$$

IV. SIMULATION RESULTS

The proposed MMCC-UPFC shown in Fig. 2 and the corresponding control schemes are verified through SIMULINK/MATLAB. The parameters of the system are listed in Table. I: Three-phase voltage rating at the sending bus is 11kV, 50Hz; the MMFCC total DC voltage rating is 12.8kV containing 32 FCC submodules in each phase, while the DC capacitor voltage per submodule is 400V and the floating flying capacitors are rated at 200V. The series converter contains one DC capacitor and its voltage rating is 800V.

TABLE I. CIRCUIT PARAMETERS

Components	Rating
3-Phase Source voltage V_s	11 kV
Transmission line impedance Z_L	6.5 Ω , 8.4mH
Fundamental frequency f_0	50 Hz
Switching frequency f_{c1}	250 Hz
Switching frequency f_{c2}	4 kHz
RL Filter	1.0 Ω , 1.0 H
SM numbers per phase	32
SM DC capacitor C_{dc}	1120 μ F
SM Flying capacitor C_{fc}	560 μ F
Nominal SM DC voltage V_{dc}	400 V
3-Phase Rated Power S	18.5 MVA
Series transformer turn ratio $n_1:n_2$	10:1
Series converter DC capacitor C_{dc_series}	560 μ F
Nominal series converter DC voltage V_{dc_series}	622 V

To validate the MMFCC-UPFC's ability in power flow control, the receiving end voltage is set to 10.45kV and phase angle 10° initially without MMFCC-UPFC, so the real and reactive power of the transmission line are 0.6p.u. and -0.3p.u from sending bus to receiving end. At 0.2 sec, the MMFCC-UPFC is switched on and the command real and reactive powers are changed to 0.71p.u. and -0.18p.u. As shown in Fig. 8, under UPFC control, the real and reactive powers transmitted to the receiving bus follow the command values closely. Similarly at 0.3sec the real power drops to 0.21p.u. and the reactive power changes to -0.25 p.u. according to the set reference values. Fig. 9 shows the corresponding UPFC real and reactive power P_c and Q_c injected to the line. Clearly the MMFCC-UPFC device can control both real and reactive powers of the transmission line to the required values precisely and fast.

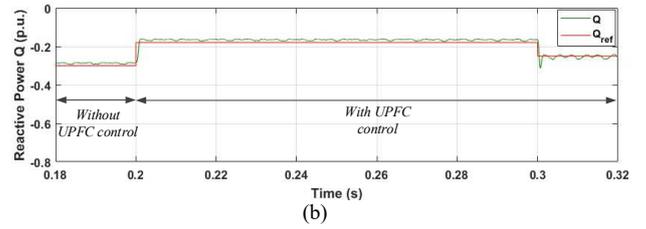
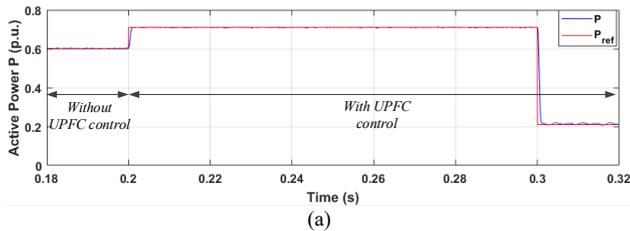


Fig. 8. (a) Transmission line (a) Real power P and (b) Reactive Power Q with their reference commands

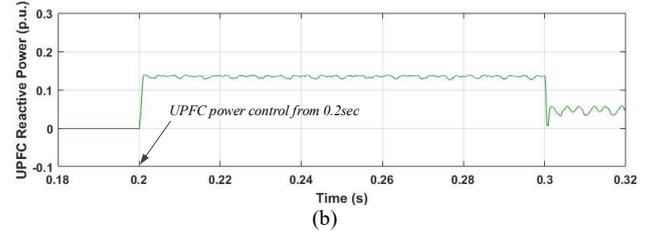
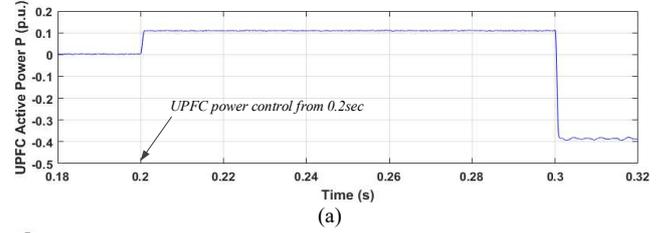
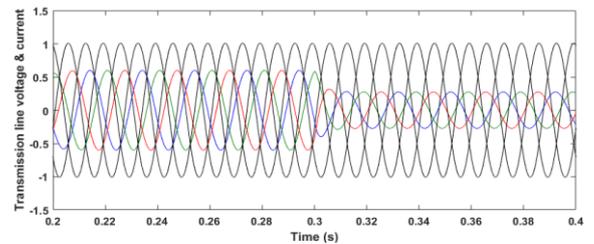


Fig. 9. MMFCC-UPFC (a) Real power P_c and (b) Reactive Power Q_c

Fig. 10 shows the corresponding 3-phase voltages with their currents of the transmission line, UPFC shunt and series part respectively. As expected, the MMFCC controls its current (Fig.10 (b)) to be equal to the difference between transmission line current (Fig.10 (a)) and series converter's current (Fig.10 (c)), which is $(\bar{I}_c - \bar{I}_l)$. At 0.3sec, the magnitude of transmission line current reduced to around 0.3 p.u. due to the changing of real and reactive power command values, consequently the series part current decreases while the shunt part current remains the same, which indicates that the control schemes of both shunt and series converters are chained well and responding fast.

Meantime, Fig. 10 also illustrates that at the steady state the AC voltages of the two converters are in quadrature with their currents hence no active power exchange in both converters, while the shunt MMFCC is inductive and series VSC is capacitive. Therefore, the MMFCC module DC capacitor voltages and the series VSC voltage are well maintained at their nominal value 1p.u. respectively, as shown in Fig. 11. Finally, the 3-phase MMFCC terminal multilevel voltage waveform is shown in Fig. 12.



(a) Transmission 3-phase voltage (black) and current

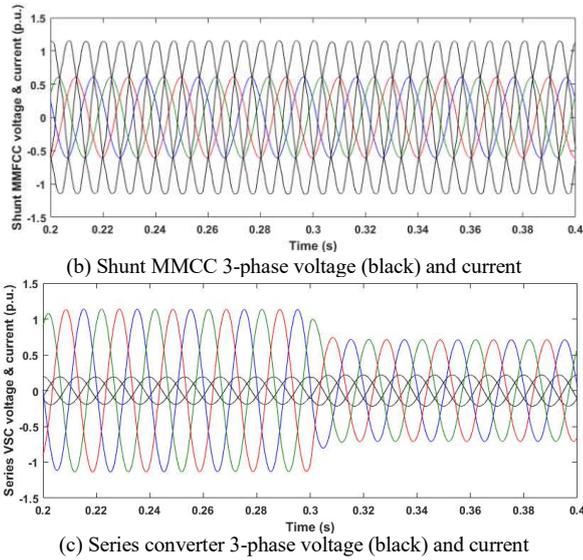


Fig. 10. MMFCC-UPFC system simulated 3-phase voltages and currents

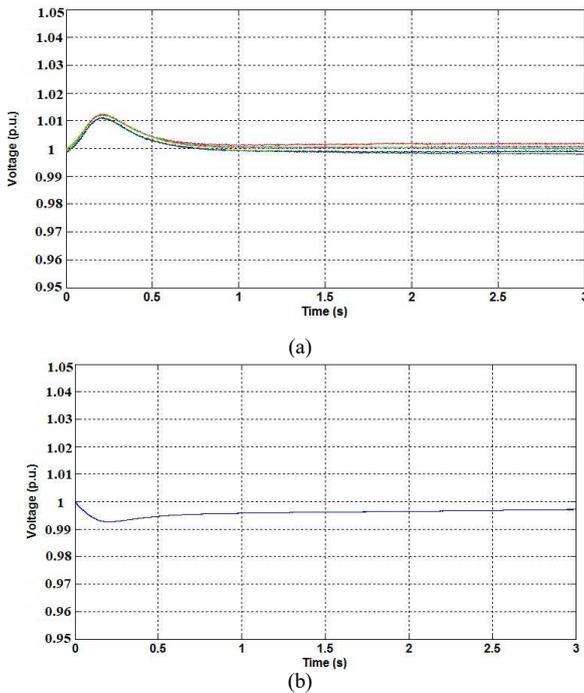


Fig. 11. (a) Shunt MMCC and (b) series converter DC capacitors voltage

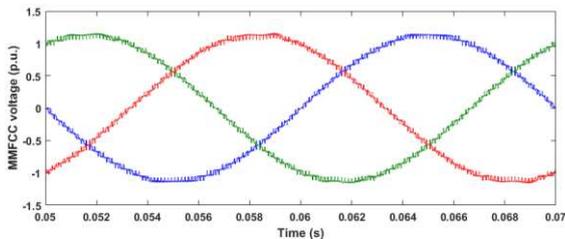


Fig. 12. 3-phase MMFCC multilevel voltage waveform

V. CONCLUSION

A modular multilevel converter based unified power flow controller (UPFC) was proposed in this paper to provide high flexibility, lower losses power flow control in the transmission system and remedy the disadvantages of conventional UPFC. The operating principle of this novel device and corresponding control schemes of the series converter voltage generation and shunt converter (MMCC) current regulation were explained. An overall DC capacitors voltage control is proposed to compensate the losses and confirm zero real power exchange between the two converters thus their DC capacitors voltage can be well balanced. Simulation results has shown that the device can react fast to control the transmission line power to the required levels.

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