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Unified power flow controller based on two shunt converters and a series capacitor

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ABSTRACT

In this paper a novel configuration of unified power flow controller (UPFC) which consists of two shunt converters and a series capacitor is proposed. In this configuration, a series capacitor is used between two shunt converters to inject desired series voltage. As a result, it is possible to control the active and reactive power flow as same as the conventional configuration of UPFC. The main advantage of the proposed UPFC in comparison with the conventional configuration is injection of a series voltage waveform with a very low total harmonic distortion (THD). Also, using two shunt converters instead of a series and a shunt converters, results in reduction of design efforts and simplification of control, measuring and protection strategies. An optimal control strategy based on the discrete model of converters is applied to shunt converters. The proposed UPFC is simulated using PSCAD/EMTDC and MATLAB software and simulation results are presented to validate the effectiveness of the novel configuration of UPFC. Also, the experimental results which are obtained from an experimental set-up are presented.

1. Introduction

The unified power flow controller (UPFC) is one of the most comprehensive multifunction flexible ac transmission system (FACTS) controllers [1,2]. It is able to control all of the parameters affecting power flow in a transmission line, simultaneously or selectively. Alternatively, it can independently control both active and reactive power flow in the transmission line [3]. In some conditions, it also acts as a harmonic isolator [4]. Normally, a UPFC consists of two voltage source converters (VSCs) which are connected back-to-back through a dc link [5–7] whereas one of them operates as a series converter and the other operates as a shunt converter [8,9]. The shunt converter of the UPFC controls the voltage of UPFC bus or its reactive power, plus the regulation of the dc link voltage [9,10]. The series converter controls the transmission line active and reactive power flow by injecting a desired series voltage which is controllable both in magnitude and phase angle [3,9]. The interaction between the injected series voltage and the transmission line current leads to active and reactive power exchange between the series converter and the power system. The shunt converter provides the active power required by the series converter plus the losses of the UPFC converters [9,11]. In [11], the active power demand of series converter is calculated and sent to the shunt converter as a compensated signal to regulate the dc link voltage during both steady and transient states. Also, the reactive power flow variations is added to the shunt converter as a compensation signal to maintain the UPFC bus voltage at a constant level or to control the reactive power of sending end when power flow changes.

The conventional power circuit topology of UPFC is based on using two 2-level-3-phase VSCs [10]. Unfortunately, it is not possible to inject sinusoidal series voltage waveform with low THD by conventional UPFC topology. There are two main alternatives to solve this problem, which are using “zigzag transformer connections” and “multilevel converters” [12,13]. The zigzag arrangement occupies large area; it is expensive and may cause difficulties in control [12,13]. Also, this arrangement results in power losses. On the other hand, as the multilevel converters satisfy THD standards without incurring the expense of inter-stage transformers [14], those seem to be a suitable candidate for UPFC configuration. Multilevel converters are generally classified as diode-clamped multilevel converters (DCMLC), cascade H-bridge converters [14–16] and flying capacitor multilevel converters (FCMLC) [17–19]. The cascade converter has not been found suitable for the UPFC applications; the reason is that connecting separate dc sources between two converters in a back-to-back arrangement (e.g., in UPFC) is not possible because short-circuit may occur when two back-to-back converters are not switched synchronously. To overcome this problem, cascade transformer based UPFC arrangement is proposed in [20]; but it uses some transformers which causes great increase in the overall cost of the UPFC. On the other hand, the DCMLC and FCMLC based UPFC structures

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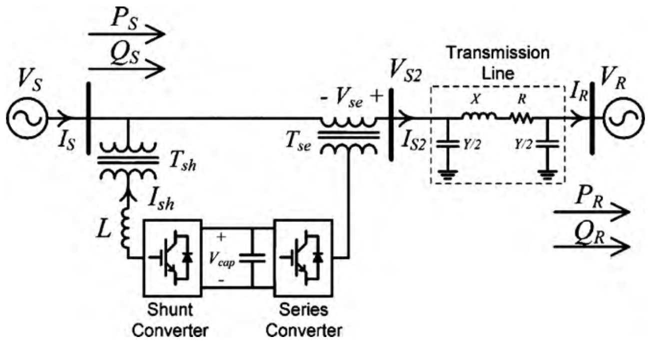

Fig. 1. Conventional configuration of UPFC.

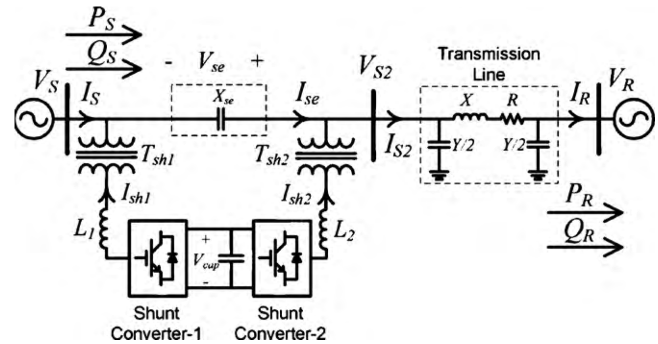

Fig. 2. Proposed configuration of UPFC.

[21,22] suffer from complicated power circuit topology and control strategy.

To overcome mentioned problems, this paper proposes a novel configuration of UPFC which consists of two shunt converters and a series capacitor. The injected series voltage waveform by this configuration has extremely low THD. The proposed UPFC is based on using only two 2-level 3-phase shunt converters and a series capacitor. So, the cost, volume and rated power of UPFC decrease and the control scheme becomes simpler than conventional UPFC configuration. Also, an online control is applied to the shunt converters. The main idea of this controller is based on optimal control theory and its main advantage is constant switching frequency.

2. System configuration

Fig. 1 shows the conventional configuration of UPFC. In this figure, transmission line is modeled as a medium length line and its parameters are defined as follows:

$\vec{V}_S$ and $\vec{V}_R$: phasor of sending and receiving end voltages (line to neutral), respectively.
$\vec{V}_{S2}$: phasor of effective sending end voltage (line to neutral) at the beginning of the transmission line.
$\vec{V}_{se}$: phasor of desired injected series voltage.
$\vec{I}_S$ and $\vec{I}_R$: phasor of sending and receiving end line currents, respectively.
$\vec{I}_{S2}$: phasor of line current at the beginning of transmission line.
P_S and Q_S: sending end active and reactive powers, respectively.
P_R and Q_R: receiving end active and reactive powers, respectively.
$\vec{I}_{sh}$: phasor of shunt converter current.
T_{sh} and T_{se}: isolation transformer of shunt and series converters, respectively.
L: equivalent inductance of $T_{sh.}$
R and X: series resistance and reactance of transmission line, respectively.
Y: parallel admittance of the transmission line.
V_{cap}: voltage of DC link capacitor.

To control the receiving end active and reactive powers (P_R and Q_R), $\vec{I}_R$, $\vec{V}_{S2}$, $\vec{I}_{S2}$ and $\vec{V}_{se}$ are calculated as follows:

$$\vec{I}_R = \left(\frac{P_R + jQ_R}{3\vec{V}_R}\right)^* \tag{1}$$

$$\vec{V}_{S2} = \left(1 + \frac{ZY}{2}\right) \cdot \vec{V}_R + Z \cdot \vec{I}_R \tag{2}$$

$$\vec{I}_{S2} = \left(Y\left(1 + \frac{ZY}{4}\right)\right) \cdot \vec{V}_R + \left(1 + \frac{ZY}{2}\right) \cdot \vec{I}_R \tag{3}$$

$$\vec{V}_{se} = \vec{V}_{S2} - \vec{V}_S \tag{4}$$

where Z is the series impedance of the transmission line.

Fig. 2 shows the proposed configuration of UPFC which consists of two shunt converters and a series capacitor. In this figure, the parameters are defined as follows:

$\vec{I}_{sh1}$ and $\vec{I}_{sh2}$: phasor of shunt converter-1 and shunt converter-2 currents, respectively.
T_{sh1} and T_{sh2}: isolation transformer of shunt converter-1 and shunt converter-2, respectively.
L_1 and L_2: equivalent inductance of T_{sh1} and T_{sh2}, respectively.
X_{se}: reactance of series capacitor between two shunt converters.
$\vec{I}_{se}$: phasor of series capacitor current.

Other parameters of Fig. 2 are same as Fig. 1.

In this configuration, the series capacitor is placed between two shunt converters to convert I_{se} to V_{se}. The calculation of optimized series capacitor (X_{se}) value to minimize the VA rating of shunt converter-2 is explained in details in Section 4. In the proposed configuration, shunt converter-1 supplies to or absorbs from utility the necessary active power to regulate the voltage of dc link capacitor. It also exchanges reactive power with utility to control the sending end reactive power. It can be noted that the operation of this converter is same as shunt converter in Fig. 1. On the other hand, shunt converter-2 tracks reference current to control the current of series capacitor to inject the desired series voltage, V_{se}. As a result, it can be pointed out that the current of series capacitor is not fixed and it can be controlled by shunt converter-2. Therefore, the power flow through the series capacitor is not fixed. It should be noted that the proposed configuration is able to have all of the capabilities of conventional UPFC. Its reason is that the main functions of conventional UPFC are injecting the desired series voltage by series converter (Fig. 1) and tracking the reference current by shunt converter (Fig. 1) in order to exchange the active and reactive powers while both of these functions exists in proposed configuration of UPFC because it is possible to inject the series voltage with any desired amplitude and phase angle by combination of series capacitor and shunt converter-2 operation as well as to track the reference current by shunt converter-1 (Fig. 2) to have the same operation of shunt converter of conventional configuration. Thus, the proposed configuration not only is non-solid state device but also it has exactly all capabilities of conventional UPFC. However, it is worth to mention that the series voltage of proposed configuration of UPFC as like as conventional one is not controllable in the case of UPFC installation between two power systems with strong connection, *i.e.* with very short transmission line or especially between two power systems with infinite bus systems and without transmission line. This subject is clear by referring to Figs. 1 and 2. These figures show that for $X = 0$ and $R = 0$ (two power systems with infinite buses and no transmission line), the voltage of series capacitor in the proposed UPFC as well as the voltage across series transformer of conventional UPFC is equal to voltage difference between two