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Control of a Novel UPFC Based on Nine Switch AC/AC Converter

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ABSTRACT

Unified Power Flow Controller (UPFC) is one of the most comprehensive FACTS devices which can controls three system parameters independently. In this paper a novel configuration of UPFC which consists of a nine-switch ac/ac converter parallel with a series capacitor has been proposed to inject desired series voltage. It means that operation of nine-switch ac/ac converter in this configuration is the same as combination of two dc/ac converter in conventional UPFC. However, proposed configuration needs fewer power electronics switches and gate drive circuits and control scheme becomes simpler than conventional UPFC configuration. using series capacitor parallel with nine–switch ac/ac converter reduce the injection voltage's THD, eliminate output filter, and reduce the converters power rating in comparison with conventional UPFC composed of series and shunt converters. The proposed UPFC is modelled using MATLAB/SIMULINK software and simulation results are presented to indicate good operation of the novel UPFC.

Key Words: *Unified Power Flow Controller, Nine Switch Converter, Two Shunt Converter*

1. INTRODUCTION

Today with the progress of power electronic, Flexible AC transmission systems (FACTS) are one of the most important technologies which is expanding more than other electric power control strategies. FACTS devices can control the power flow in transmission line, regulate voltage at the point connection to network and compensate reactive power. Also FACTS devices can utilize in power system damping enhancement because they have acceptable time response to damp oscillations. As mentioned advantages the uses of FACTS are increasing of voltage regulation, power transferring capability, and damping of power oscillations [1]-[3].

Most comprehensive device in the FACTS concept is the unified power flow controller (UPFC). It can adjust the three control parameters of system simultaneously and independently. The transmission line reactance, bus voltage, and phase angle between two buses are

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parameters can be control using UPFC. The conventional UPFC is composed of two voltage source converters, one of them is connected in series with power system network and other in shunt and both are connected back to back through a DC link [4].

Active and reactive power flows on the transmission line can be controlled by series converter. The series converter injects a symmetrical three phase voltage series with the line, because of magnitude and phase angle of injected voltage are controllable this converter will exchange active and reactive power with the line. The shunt converter regulates the DC link capacitor voltage and also used to provide voltage regulation at the connection point by exchanging reactive power with the line [5].

Due to the conventional UPFC is based on using two 2-level-3-phase voltage source converters, it cause problem which the injected series voltage is not a sinusoidal waveform with low THD and output filters are essential. UPFC based "zigzag transformer connections" and "multilevel converters" are two options to solve this problem which reported in [6,7].

Zigzag arrangement solve THD problem but increase the cost, volume, power loses and also control of this structure is difficult. On the other hand, multilevel converters require complex circuit and control strategy to satisfy THD standards.

To overcome mentioned problems, recently [8] proposes a novel topology of UPFC which is consists of two 3-phase back-to-back shunt converters and a series capacitor. In this topology the cost, volume and rated power of UPFC is decreased. Also both of converters are connected in parallel with line so the control scheme becomes simpler than conventional UPFC, and more important than aforementioned advantages of this configuration is reduction of injected voltage THD [8]. In this topology 2-level 3-phase back-to-back converter has been used, so it requires twelve power electronic switches. Recently the novel nine-switch converter has been introduced as a good alternative to existing 3-phase back-to-back converters in [9-12] as shown in Figure 1. In comparison with back-to-back converters, the proposed nine-switch converter uses fewer number of power electronic switches which reduces the cost. This paper present a novel UPFC based on two parallel connections and a series capacitor. In proposed UPFC the novel nine-switch converter has been used instead of back-to-back converter so the number of power electronic switches reduced from twelve to nine in comparison with reported topology in [8].

In this paper first a new nine-switch converter is introduced and the carrier based PWM switching algorithm for this converter has been considered. Novel UPFC based on nine-switch converter is explained in next section. Simulation results on proposed UPFC are provided to confirm operation of proposed structure.

2. NINE SWITCH AC/AC CONVERTER

The nine-switch converter has three legs with three switches per leg as shown in Figure 1. In back-to back converters one of the converters act as a rectifier and other acts as an inverter. In nine- switch converter due to the middle switch is shared by rectifier and inverter, the number of switches reduces in comparison with back-to-back converter. Also the nine-switch converter can be used as an ac/ac converter [9-12].

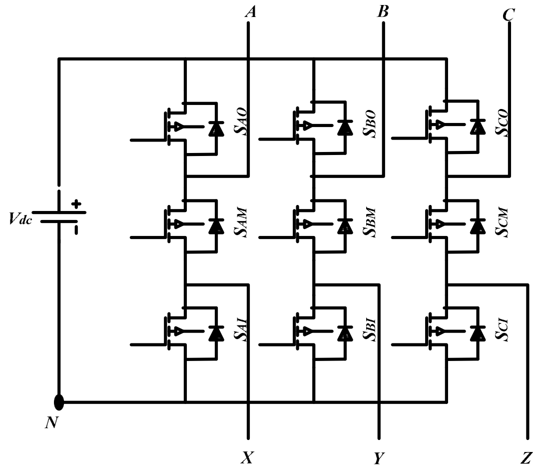


Figure 1. Structure of nine-switch ac/ac converter.

The input and output voltages in nine-switch converter can be controlled independently like back-to back converter although this converter has fewer number of switches.

Switching states for nine-switch converter are given in Table1. It is considered that this converter has three valid states per phase. Voltages at nodes are shown with V_{AN}, V_{XN} (voltages of A and X respect to the negative dc link (N)).

In this paper it is assumed that A, B, C are the output nodes and X, Y, Z are the input nodes of the nine-switch converter.

Table 1. Converter output voltages and switches states

state	ON Switches	Voltage of input and output nodes
1	S_{AM}, S_{AO}	$V_{AN}=V_{dc}$, $V_{XN}=V_{dc}$
2	S_{AI}, S_{AM}	$V_{AN}=0$, $V_{XN}=0$
3	S_{AI}, S_{AO}	$V_{AN}=V_{dc}$, $V_{XN}=0$

As mentioned to switch a nine-switch converter the carrier based PWM control method is used [9]-[12]. To obtain gate signals in each phase there are two reference signals as shown in Figure 2. The gate signals for upper and lower switches are obtained as follow:

State 1: $S_{e1}>C$ then S_{AO} is on

State 2: $S_{e2}<C$ then S_{AI} is on

$S_{e1}$and S_{e2} can be expressed as:

$$S_{e1} = A_{out} \sin(2 * \pi * f_{out}) + b_{out} \quad (1)$$

$$S_{e2} = A_{in} \sin(2 * \pi * f_{in}) + b_{in} \quad (2)$$

Where A_{out}, A_{in} are the modulation index, f_{out}, f_{in} are the output and input frequency respectively, and b_{out}, b_{in} are the offset of output and input references signals respectively. For switching middle switch in each phase, the gate signals is generated by the logical NAND of gate signals for the upper and lower switches as shown in Figure 3.

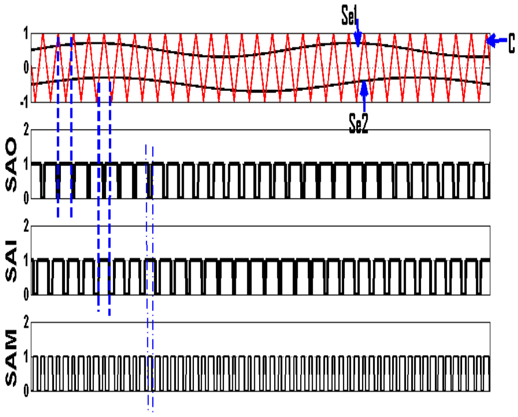


Figure 2. PWM waveforms for nine switch converter.

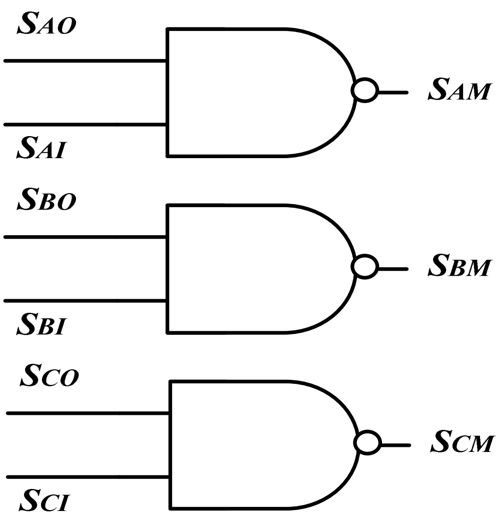


Figure 3. Circuit to generate middle switches gate signals.

3. PROPOSED UPFC BASED ON NINE-SWITCH AC/AC CONVERTER

A traditional UPFC to control active and reactive power flow transmission simultaneously is composed of series and shunt converters which are connected back-to-back with common dc-link capacitor as shown in Figure 4.

The shunt converter of the UPFC controls the voltage of UPFC bus or its reactive power, also it regulate the dc link voltage. 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 [13].

The series converter injects voltage to transmission line, by changing injected series voltage active and reactive power exchange between the series converter and the power system. Active power required by the series converter plus the losses of the UPFC converters has been provided by the shunt converter [14]-[15].

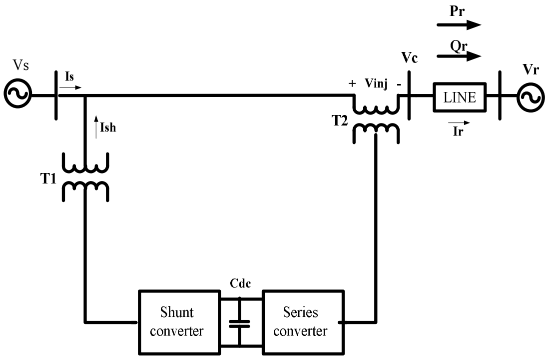


Figure 4. Conventional UPFC consist of shunt and series converters

Figure 5 shows the proposed configuration of UPFC which consists of a nine-switch ac-ac converter and a series capacitor.

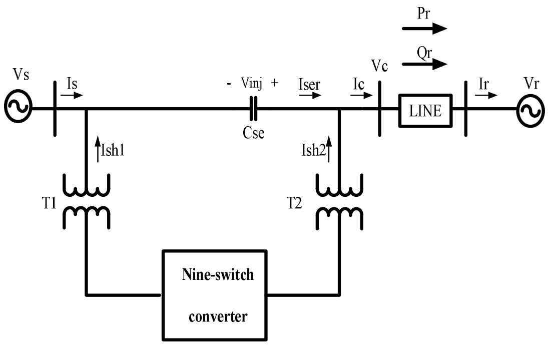


Figure 5. Proposed UPFC based on nine switch converter

In [8], a series capacitor has been used in parallel between two shunt converters which desired injection voltage to control active and reactive power has been injected by this capacitor, using this configuration reduce THD, eliminate output passive filter, and also reduce converters power rating compared with the conventional UPFC consist of series and shunt converters [8].

In proposed UPFC in this paper, a nine-switch ac-ac converter has been used instead two dc-ac converters in novel UPFC [8] based on two shunt converters and a series capacitor. As mentioned in this converter, the input and output voltages can be independently controlled then it can be noted that the operation of nine-switch ac/ac converter in this configuration is the same as combination of two dc/ac converters in conventional configurations.

The main advantages are that proposed UPFC has less number of switches and also it has simple control circuit. For regulating the dc link voltage nine-switch converter supplies to or absorbs the necessary active power. It also exchanges reactive power with utility to control the sending end reactive power. Nine-switch converter tracks reference current of series capacitor to inject the desired series voltage, V_{inj}.

Considering Figure 5, the power flow equations of system would be as follow:

$$P_r + jQ_r = 3V_r I_r^* \qquad (3)$$

$$V_c = V_r + ZI_r \qquad (4)$$

$$V_{inj} = V_c - V_s \qquad (5)$$

Where sending voltage end, receiving voltage end, and injection voltage are shown as V_s, V_r, V_{inj} respectively. P_r, Q_r are receiving active and reactive powers and Z is the series impedance between receiving end and sending end. Figure 6 illustrates phasor diagram of proposed system configuration, in this figure, the phase difference between the sending end and the receiving end voltages are named θ.

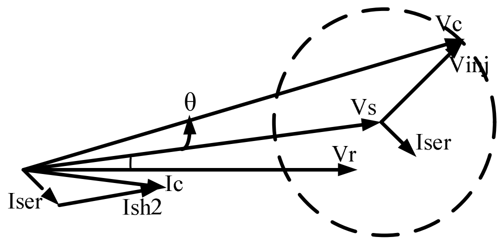


Figure 6. Phasor diagram of power system

Considering Figure 5 and Figure 6 Magnitude and phase of injection voltage can be controlled by changing I_{sh2} that generated with nine-switch converter as follow:

$$\begin{aligned} V_{inj} &= j(1/2\pi fC_{se}) * I_{ser} \\ I_{ser} &= I_c - I_{sh2} \end{aligned} \qquad (6)$$

By controlling I_{sh2} in (6) using converter, I_{ser} is controlled, as a result V_{inj} is controlled with nine-switch converter. Then phase and magnitude of V_c are controllable with V_{inj} similar to conventional UPFC, so active and reactive powers can be controllable simultaneously.

The circuit diagram to control active and reactive power flow transmission using proposed UPFC has been illustrated in Figure 7.

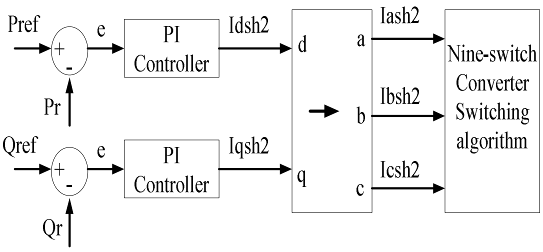


Figure 7. Circuit diagram to control active and reactive power

In this strategy, the error between desired active and reactive power with real active and reactive power generated references currents of nine-switch converter. Figure 8 shows the other control loops to keep the DC link voltage constant, and regulate sending end voltage.

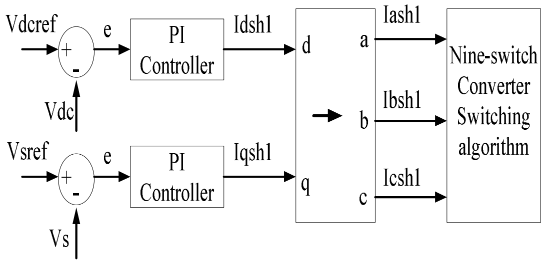


Figure 8. Circuit diagram to control DC link and sending end voltages

The output current signals from controllers are used as references signal in the carrier based PWM algorithm to switch the nine-switch converter.

4. SIMULATION RESULT

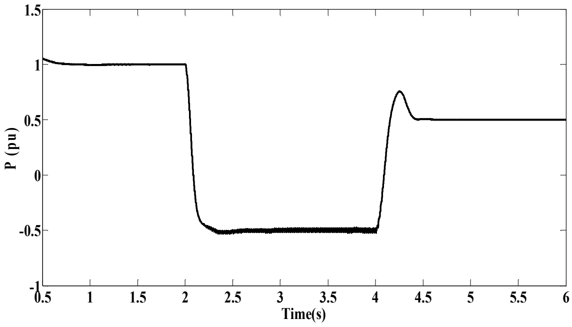
MATLAB/SIMULINK has been used to model proposed UPFC and simulation results presented to show the performance of novel structure. The main parameters used in simulation are listed in Table 2.

Table 2. Main parameters of simulated system

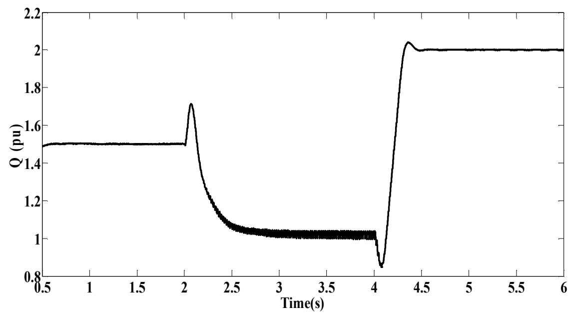
System parameters	values
Base voltage of power system (KV)	20
Base power (MW)	20
Frequency (Hz)	50
Sending voltage (phase-phase) (KV rms)	38∠0°
Receiving voltage (phase-phase) (KV rms)	36∠-5°
frequency of nine-switch converter carrier(KHz)	1
Series resistance of line (Ω)	5
Series reactance of line(Ω)	25
Turn ratio of isolation transformers	4
DC-link capacitor (mF)	1
Series capacitor (mF)	0.124

Figure 9 show the active and reactive power, the operation of the proposed UPFC has been evaluated by sudden changing in the active and reactive power references. Initial reference values are set to P_r=1pu, Q_r=1.5pu for active and reactive powers respectively. At t = 2 s the reference values are changed to P_r =−0.5pu, Q_r = 1pu, also at t=4 s the reference of active power has been changed to P_r=0.5pu and the reference of reactive power has been changed to Q_r=2pu. It is considered from Figure 9. Active and reactive powers of receiving and sending end can be controlled using the proposed UPFC. When power flow is negative, it shows the power flow in the line is reversal.

Figure 10.(a) shows injected series voltage by series capacitor in normally conditions, As shown in this figure active and reactive power changing at t=2s results in injection voltage changing in this time, also this process is repeated at t=4s by changing active power and reactive power.

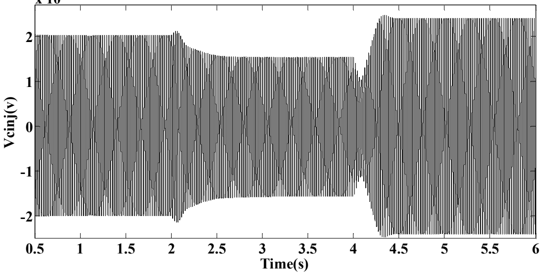


(a)

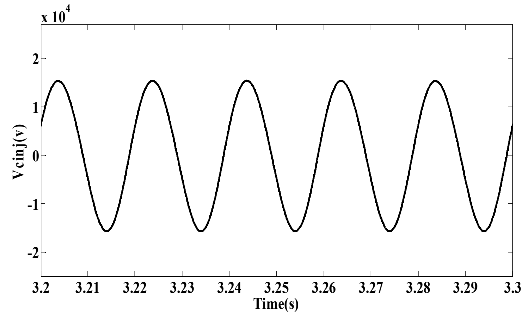


(b)

Figure 9. Receiving powers: (a) active power (b) reactive power



(a)



(b)

Figure 10. Injected series voltage by capacitor: a) during all simulation time, b) during short time to show sinusoidal series voltage.

Figure 10. (b) is magnified of Figure 10.(a) which shows the novel UPFC can inject series voltage near to sinusoidal waveform with a low THD without any output ac filters.

Figure 11 indicates harmonic spectrum of injected voltage by series capacitor, as shown in this figure fundamental voltage (reference voltage) has been generated, and other order harmonics are very low then size of output filter is very small. So injection transformers are as a filter for voltages of nine-switch converter in this application.

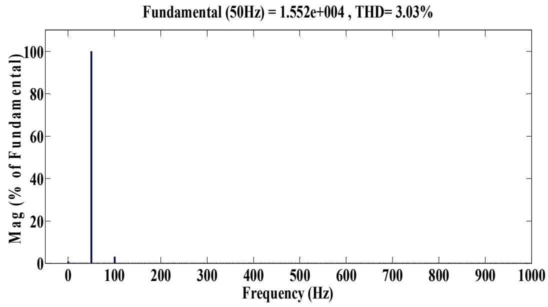


Figure 11. Harmonic spectrum of injected voltage

DC link voltage is shown in Figure 12. The DC link voltage is almost constant and variation of it in comparison with DC level is very low and negligible. So in transient and steady states the DC link voltage is considered almost 0.6pu (12kv) in this simulation.

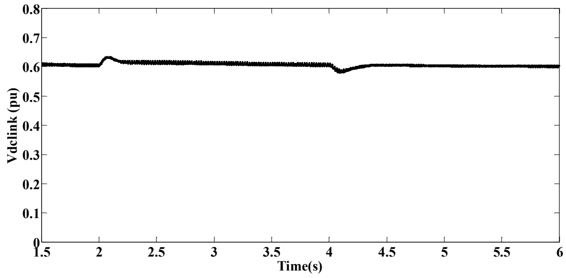


Figure 12. DC link voltage of nine switch converter

Simulation results show the proposed UPFC consist of a nine-switch converter instead of two dc-ac converter controlled the active and reactive power flow in transmission line as well as the conventional UPFC with reduced power semiconductors devices.

5. CONCLUSION

This paper proposed a novel UPFC employing novel nine-switch ac/ac converter. The suggested configuration needs fewer switches and gate drive circuits. Therefore, the proposed topology results in reduction of installation area and cost. Also, PWM based switching algorithm has been presented for novel converter. Besides, control strategy of UPFC based on a suggested converter was described. The simulation results show that the proposed UPFC can operate according to control strategies against in the active and reactive power references sudden variations.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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