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ORIGINAL PAPER

Wide area voltage sag control in transmission lines using modified UPFC

Soheil Ranjbar[1]

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Abstract
A modified conceptual structure of MUPFC for controlling the voltage sags in interconnected power systems is presented in this paper. For this purpose, the conventional UPFC is distributed through several series and one shunt converters. By this way, the higher frequency components are removed which only the 3th-order is remained. Also, by using single-phase series converters, better dynamic performances with proper reliability are provided. So, there are more redundancy possibilities through different operating conditions. The proposed single-phase series converters are floated from the ground which there is not required high-voltage protections equipment through transmission lines resulted in lower initial and operational costs compared to conventional UPFCs. Real-time ability of the proposed scheme is investigated through a 3-phase transmission line stressed by fault events in which by distributing the series converters through the line, the ability of MUPFC through time domain simulations is evaluated. Results present proper performances of the proposed controller scheme for voltage sags fast restoration with high damping ratio.

Keywords Power control · Transmission line · Voltage sag · Harmonic

Abbreviations

FACTS	Flexible AC transmission systems
MUPFC	Modified unified power flow controller
PE	Power-electronic
PLL	Phase-locked loop
SSSC	Static synchronous series compensator
STATCOM	Static synchronous compensator
UPFC	Unified power flow controller

1 Introduction

Increasing power demands and network structures in power system resulted in difficult to control and management of the active and reactive powers follow in inter-connected transmission lines and hence maintain the system stability criteria [1]. By innovating FACTS equipped with a series of PE devices, it is possible to control the transmission lines parameters and power transactions with proper stability criteria [2]. In this case, UPFC known as one of the powerful devices which control the transmission line parameters using the bus voltages, angles and line impedances [3]. Simple view of UPFC structure is shown in Fig. 1. As it can be seen, UPFC is made through combining a SSSC and a STATCOM connected together through a dc link. By this way, a two-side active power can be exchanged through the shunt and series output terminals of the STATCOM and SSSC, respectively [4].

The PE converter in series part of UPFC plays as the main section by providing multi-amount of voltage and controlling the voltage phase and magnitude. The provided voltage mainly plays as a voltage source that is implemented to adjust the transmission line and angle. By this way, the reactive and active power can be controlled independently within the line.

The series part of UPFC can injects the reactive and active power to the system or absorbs two related power through the series capacitor and the line. In this case, active power is generated by the UPFC shunt section connected back-to-back to the series section.

Also, it can be deducted that the required reactive power is supplied through series section as the same as SSSC device

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✉ Soheil Ranjbar
s.ranjbar@velayat.ac.ir

[1] Department of Electrical Engineering, Velayat University, Iranshahr, Iran

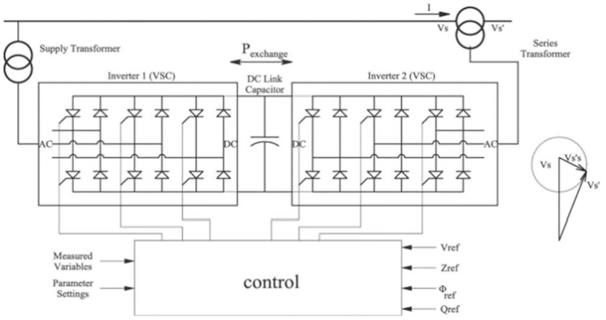

Fig. 1 Simplified UPFC structure

[5]. In fact, shunt is responsible to adjust the dc link voltage through generating/absorbing output active power. Hence, it plays as a parallel synchronous with the system. Also, same as STATCOM, UPFC shunt part compensate reactive power for improving the bus voltage. Since, for controlling both currents and voltages, all UPFC sections are involved so, in wide ranges, the installation cost of UPFC is too high and expensive. Since the conventional UPFC has one common dc link, so a fail at series or shunt converters will be influence directly at the whole of the system. To increase the power system reliability in the presence of converter failures, such redundant backups and bypass circuits (e.g. backup transformers) are necessary, which caused to increase the overall cost of the system. Despite the controlling capabilities and the benefits UPFC for enhancing power system security, it has been less used commercially in power system due to high prices.

This paper presents a modified concept of UPFC, called as MUPFC which is made from the conventional UPFC with lower cost. Similar to UPFC, MUPFC is capable to control and adjust all of the system parameters. In this case, the common dc link is eliminated between the series and shunt converters which lead to decrease in cost of the system. In this case, the active power interchange between the series and shunt converters is within the lines at the 3th-harmonic frequency. In the proposed scheme, the series part of UPFC is distributed through the transmission lines by implementing multiple single-phase series converters [6]. In Comparing with the conventional UPFC, the proposed MUPFC has two main advantages including: (1) low overall cost in the system because of the single-phase series converters in transmission lines and (2) high security and reliability because of the multiple numbers of series converters in system.

This paper is organized as follows; in Sect. 2, the principle and design of the proposed scheme is presented. Then in Sect. 3, the controlling region of is presented from which the steady state analysis MUPFC is also discussed. In Sect. 4, a short introduction about the MUPFC Control is presented and finally in Sect. 5, the MUPFC ability in the presence of converter failure is analyzed by introducing simulation scenarios in time domain.

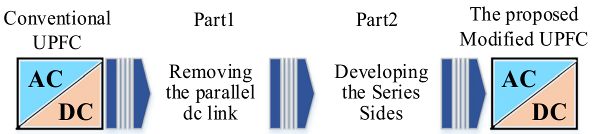

Fig. 2 The procedure of conversion UPFC to MUPFC

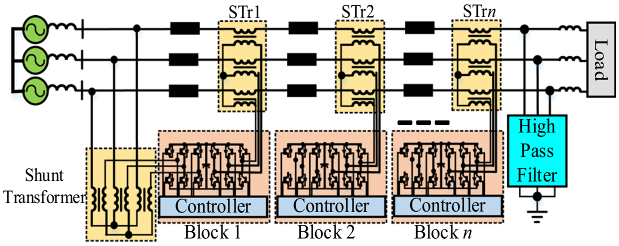

Fig. 3 MPUFC internal structure

2 Mechanism of inter-area oscillations

In this paper, two different approaches are implemented for UPFC to enhancement the system security and decrease the cost as follows. First, the common dc link between the series and shunt converters of the UPFC are eliminated and then the series part is distributed in transmission line as shown in Fig. 2. As it is illustrated in Fig. 2, by implementing two proposed approaches, a modified UPFC is designed as MUPFC.

The proposed MUPFC consisting of one shunt converter and various distributed series converters. In this case, the shunt part works as a STATCOM, while the series part works as MUPFC concept, which is consisted several single-phase series converters instead of one large scale converter. In this scheme, each series distributed converter in MUPFC works as an independent converter from which has own specified capacitor to prepare the required controlling voltage. The structure of the MUPFC is shown in Fig. 3. As illustrated in Fig. 3, besides two main series and shunt converter parts, the MUPFC also needs two transformers in Y-Δ connection and two high-pass filters connected parallel at the both sides of the transmission line. The reasons for these require components are explained in Sect. 2 -part A. The control strategy of conventional UPFC is works by connecting the series and shunt converters in back-to-back connection, which permit to flow and exchange the active power in lines freely.

In order to evaluate similar control strategy through MUPFC and UPFC, the proposed method is investigated by eliminating the dc link and analyzing the interchange of active power within the converters.

2.1 Eliminate the common DC link

In the proposed MUPFC shown in Fig. 3, it can be seen a common connection between the series single-phase converters and ac part of shunt converter that is one transmission line. By this way, the active power can be exchanged within the ac part of the converters through the lines. The main principle is based on the calculating nonsinusoidal components of active power through the lines. According to Fourier series, a nonsinusoidal current and voltage can be provided by some sinusoidal equations in several frequencies with multiple amplitudes. The calculated active power resulted from these nonsinusoidal currents and voltages are defined as the average amount of the multiplying current and voltage. Since the summation of all product terms with several frequencies are going to zero, so the related active power can be explained as follows.

$$P = \sum_{i=1}^{\infty} V_i I_i \cos \phi_i \qquad (1)$$

From (1), I_i and V_i are the current and voltage for ith harmonic component respectively, and φ_i is the related angle between the current and voltage. Also, (1) explains the active power at several frequencies which are independent from each other and the related current and voltage at each frequency has no impact on the injected active power at other frequencies components. By this way, active power generates on several frequencies using series converters and receives the power from another frequency without require to source of frequency. By implementing the proposed method for MUPFC, the shunt part can receive the active power from the network at the reference frequency and generate the current within the network at another frequency component. This harmonic component of current will going within the related transmission line. Relevant to value of the needed active power at the reference frequency, the MUPFC series distributed converters inject a voltage at another frequency which leads to absorb the active power from other harmonic components. By assuming converter has no any losses, the active power injected at reference frequency will be equaled to the power received from the ith harmonic component. Figure 4 shows the proposed principle for exchanging the active power within the series and shunt converters in the proposed MUPFC scheme.

As it is illustrated, the specified high-pass filter impresses the reference frequency to flow the harmonic frequency components through the line. In this case, there is a return way for harmonic frequency components. The series and shunt converters, ground connection and high-pass filter implement as closed loop circuit for the current harmonic components. Because of the unique specifications of 3th-harmonic components, it is considered to interchange the active power in MUPFC. By this way, the 3th-harmonic component is identical in each phase and provided through zero sequence.

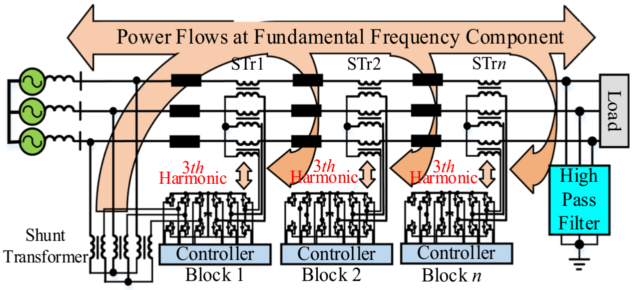

Fig. 4 Active power interchange within MPUFC converters

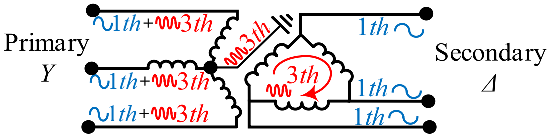

Fig. 5 Transformer connection for eliminating the 3th-harmonic component

In this case by installing two Y–Δ transformers that are vastly used in power systems to convert the voltage level, at both sides of converters, the related zero-sequence component is blocked. Hence, by this way no additional filter is required to limit the harmonic components in the rest of the grid. In fact, by providing the 3th-harmonic component in the lines as shown in Fig. 4, the related high-pass filters are replaced by low cost cables which are connected within the neutral point of transformer and the ground as shown in Fig. 3. Due to Δ connection in transformers becomes open circuit to the 3th-harmonic current, all harmonic components as shown in Fig. 5, will be going within the Y-connection and centralize into the related grounding cables. By this way, the require high-pass filter will be eliminated.

Also there is another advantage for using the 3th-harmonic component to interchange active power through the lines. By using 3th-harmonic components, the grounding path of Y–Δ transformers can be implemented to flow the different harmonic currents in a meshed grid. On the other hand, when a branch is required to flow the harmonic currents to the ground, the specified point of transformer at other side of the system is grounded and vice versa. Figure 6 illustrates the path of harmonic current into the ground by using a grounded Y–Δ transformer. Since the main transformers in the line are floating without using the series converter so the path for flowing the 3th-harmonic components is open circuit. Hence, by using the proposed scheme, the 3th-harmonic current will not flow within the transmission lines.

Mathematically, the 3th, 6th and 9th harmonic components are in the part of zero-sequence which can be used to interchange active power in the proposed MUPFC. Based on

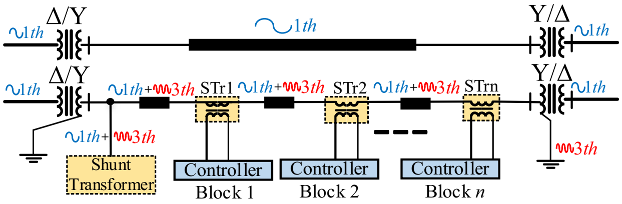

Fig. 6 Path of the 3th-harmonic using the two Y–Δ transformers

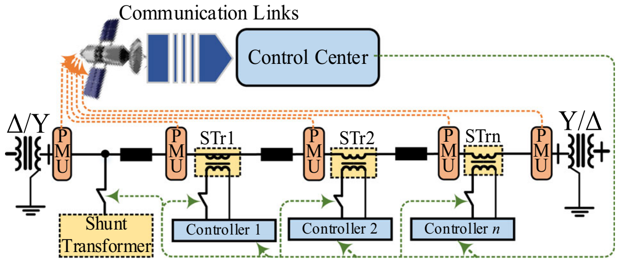

Fig. 7 MUPFC configuration and control [7]

power swing equation, the capability of transmission lines for transferring the power is related to its impedances. Since in transmission lines the inductive impedance is much more than the resistance impedance so the line impedances are depends on the frequency and transmission in high frequencies will be resulted to high impedances. Therefore, in the proposed scheme, for transferring the active power, the 3th-harmonic component is selected which resulted to the lowest impedances in transmission lines.

2.2 Distributing the series converter

The proposed MUPFC is a method for distributing the series converter in UPFC which leads to reduce the overall cost and enhance the system reliability. The idea of the MUPFC is to implement a number of series controllers in low-voltage level instead of one large-size series controller. The related small-size controllers are single-phase that are connected to the lines by individual single-phase transformers. The series converters are distributed through the transmission line from which no expensive high-voltage protection elements as isolation devices are required. The single-phase transformers connected to transmission line in the form of secondary winding which insert adjustable impedances into the transmission line directly. In fact, each series converter module is self-supplied from the transmission line and supervises distantly by power-line communication or wireless as shown in Fig. 7. The proposed configuration of the MUPFC outcomes to high reliability with low cost. As distributed series converters are single-phase units that are floating over the line, there are no high-voltage isolations elements required within the phases. Also, because of the floating the converters, it is not required any single-phase to ground isolation and therefore the series units can easily be implemented at any voltage level in transmission line. In this scheme, the rate of voltage and power of each series distributed converter is small which can be clamped on the lines any land is not required.

The distributed principle of the MUPFC obtains a continuous operation in power system in the presence of single series failures which provide higher security and reliability than conventional UPFC devices.

2.3 The MUPFC advantages

The proposed distributed controller can be implemented as conventional UPFC controller to provide the concept of interchanging active power within the 3th-harmonic component. Hence, MUPFC is included all UPFC advantages can be explained as follows.

(1) *High controllability.* Using MUPFC, the power system parameters including voltage amplitude, voltage angle and the line impedance are controlled. The deletion of dc link between two series and shunt converters provides the separated series converters in the system. The series and shunt converters can be installed at the most benefit locations. Since MUPFC has the high control availability, it can be applied to increase the power quality, restoration of voltage sag and balancing the asymmetry loads. It can also be applied to enhance the system stability such as transient stability or damping low-frequency oscillation [8].

(2) *High security and reliability.* Distribution of the series single-phase converters results in higher reliability compare to conventional UPFC because the series and shunt converters are independent against to each other and converter failures at every side will not impact on other distributed converters. Also, in the case of occurring destruction on series converters, the bypass protection is activated and the failed series converter is short-circuited. In this case, the faulted converter has no influence to the grid. In another case, when a failure occurs in shunt converter, it is open-circuited and trip from the network. In this case, series part will be stop to provide the active power and works as a distributed series controller [9].

(3) *Low cost.* Since the series converters are distributed in transmission lines in single-phase voltage level so no high-voltage protection elements required for insolating the converters. Further, each series converter presents a portion required damping power in which can be easily installed on transmission lines.

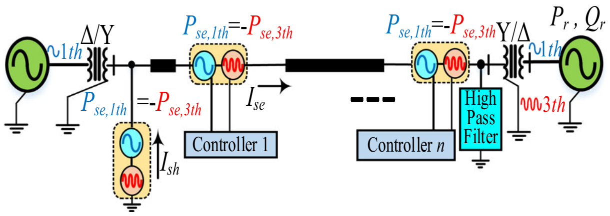

Fig. 8 MUPFC electrical circuit representation

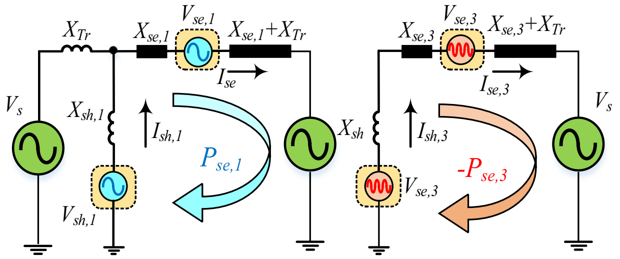

Fig. 9 MUPFC equivalent circuit from base to 3th-harmonic frequency

However, the MUPFC generates additional current at 3th-harmonic component through the transmission lines, there are some extra losses in the lines and transformers.

3 Evaluating the proposed MUPFC

In this section, the steady-state and control strategy of the proposed MUPFC are expressed. In this case, the series converters are equalled with voltage sources which control the series impedance. Based on the proposed scheme, each series converter injects the voltage in two fundamental and harmonic frequencies, so in the electrical circuit represented in Fig. 8, each converter is equalled by two different series voltage sources, one for generating the voltage at reference frequency and the other once at the 3th-harmonic frequency.

By assuming that the lines and the converters are lossless, the total active powers injected by the two different voltage sources are going to zero. The specified series single-phase converters are equalled as one large-size converter in the form of voltage source from which the generated voltage by this source is equal to voltage generated by all series single-phase converter, as shown in Fig. 8.

In Fig. 8, the MUPFC is installed in a 2-bus test system with the receiving and sending voltages V_r and V_s, respectively. Also one transmission line is specified which is equalled by a line current I and an inductance L. The multiple voltages generated by series MUPFC converters are shown as $V_{se,1}$ for fundamental frequency and $V_{se,3}$ for the 3th-harmonic frequency. Also one shunt converter is installed at sending bus which represented by inductor L_{sh}, one injected shunt current as I_{sh} and two different voltages as $V_{sh,1}$ and $V_{sh,3}$, respectively. Finally the reactive and active power, flows the powers in the line are shown as Q_r and P_r, respectively. This electrical current represents both reference and 3th-harmonic frequency components. Also it can be possible to split the circuit in Fig. 8 into two simplified circuits at different frequencies components. In this case, it is illustrated that two different frequency circuits are isolated from each other which generated active power from each converter is the only common link between two circuits as shown in Fig. 9.

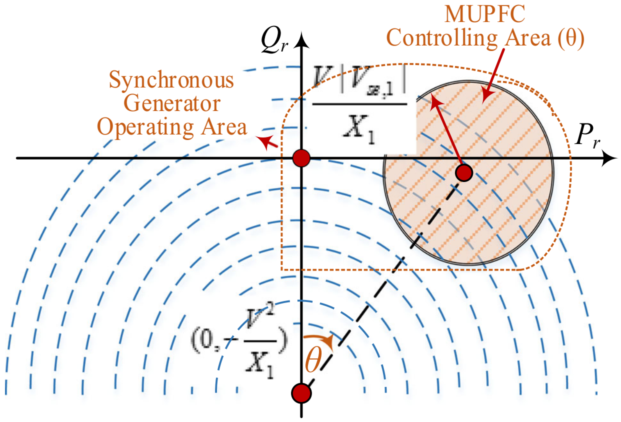

Fig. 10 MUPFC power controlling range according to transmission angle θ

The power flow controllability of MUPFC can be defined by the reactive power Q_r and active power P_r at the end of electrical circuit shown in Fig. 8. Since the proposed MUPFC behaviour at the reference frequency is the same as UPFC so the reactive and active power flowing in the transmission line can be explained as follows [1]:

$$(P_r - P_{r0})^2 + (Q_r - Q_{r0})^2 = \left(\frac{|V||V_{se,1}|}{X_1}\right)^2 \tag{2}$$

where Q_{r0}, P_{r0} and are the initial value of reactive and active power flow with acting MUPFC. X_{se}, $1 = \omega$Lse is the impedance of transmission line at reference frequency, and $|V|$ is the voltage amplitude at both end sides of system.

Actually, (2) is a circle equation which the locus of circle without using MUPFC compensation is a circle with radius $|V|2/|X_1|$ and centers $P = 0$ and $Q = |V|2/|X_1|$. Without compensating MUPFC, each location in this circle corresponds with a P_{r0} and Q_{r0} amounts with specified transmission angle θ. The border of the available controlling range for Q_r and P_r is achieved by overall rotation of the related voltage $V_{se,1}$ according to its maximum amplitude. Figure 10 illustrates the control boundary of the MUPFC depend on the transmission angle θ.

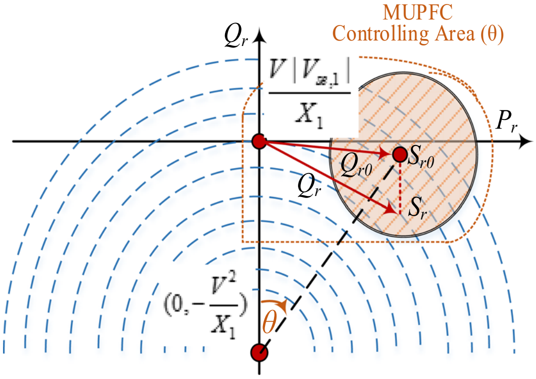

Fig. 11 Relation among Pse,1 and power flow for a fixed angle θ

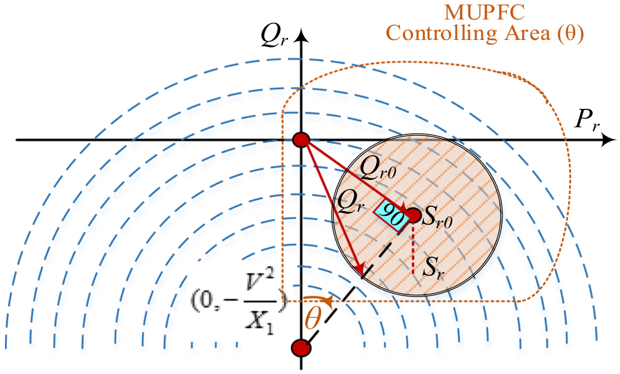

Fig. 12 Maximum requirement of active power for the series converters

To ensure that series converters are able to generate a 360∘ controlling voltage, a reactive and active power is required at the reference frequency. In this case, the active power is generated by the shunt converter and reactive power is injected by the individual series converters locally. The mentioned active power can be expressed by

$$(P_r - P_{r0})^2 + (Q_r - Q_{r0})^2 = \left(\frac{|V||V_{se,1}|}{X_1}\right)^2 \tag{3}$$

where ϕ_{r0} is the initial angle of power at the end of system without using MUPFC is equal to $\tan - 1(P_{r0}/Q_{r0})$ and ϕ_r is the angle of power at the end of system by implementing MUPFC. The voltage amplitude $|V_r|$ and line impedance X_1 are constant therefore an active power is proportionate to $|S_r||S_{r0}|\sin(\phi_r\, 0\, \phi_r)$ that is greater than the triangle area which is curved by vectors S_r and S_{r0}. Figure 11 shows the relation among $P_{se,1}$ and the power flow at the end of system for a fixed angle θ.

From Fig. 11, the active power is required by the series converter can be expressed as follows:

$$P_{se,1} = C\,A(0\,,\, r0,\, r) \tag{4}$$

where the correlation coefficient C is equal to $2X_1\,/|V_r|^2$ and the area $A(0, \mathrm{r}, 0, \mathrm{r})$ is the triangle area of $(0, S_r, 0, S_r)$.

The difference $\phi_{r0} - \phi_r$ is negative or positive which indicates the power flow directions of series converters. In the case of positive differences, series converters inject active powers at the reference frequency. Also, in the case of negative values, the powers are absorbed. In fact, the maximum power exchanges are occurred when the difference vector $S_r{-}S_{r0}$ is vertical to vector S_{r0} as showed in Fig. 12.

Based on Fig. 12, the relation among the controlling range of power flow and the maximum requirement of active power can be expressed by

$$P_{se,1,max} = \frac{|X_1||S_{r0}|}{|V_r|^2}|S_{r,c}| \tag{5}$$

where |Sr,c| is the controlling range of MUPFC.

As expressed previously, each converter in MUPFC injects two different voltages that are generated at the same time. Based on the voltage rating generated by each converter, the maximum voltage rating is equal to summation of the voltage in two different frequencies component as follows.

$$V_{se,\,max} = \left|V_{se1,\,max}\right| + \left|\mathrm{V}_{se3,\,max}\right| \tag{6}$$

Through different operating conditions, the converter power requirements are depend on the 1th order voltage values. In the case of small values, the voltage of 3th-order $V_{se,\,3}$ is lower than $|V_{se,\,3,\,max}|$. In this case, a value within $|V_{se,\,3,\,max}|$ and $V_{se,\,3}$ can be used to adjust the power flow at reference frequency and increase the MUPFC controlling boundary. When $S_{r,c}$ is vertical to the vector S_{r0}, the series converters need the maximum active power which the radius of MUPFC controlling boundary is expressed as follows.

$$|S_{r,c}| = \frac{|V_r||V_{se,1,max}|}{X_1} \tag{7}$$

In (7), when Sr,c in the line is equal to Sr0, only reactive power is provided by series converters and the region of the MUPFC controlling boundary will be extend to

$$|S_{r,c}| = \frac{|V_r|(|V_{se,\,1,\,max}| + |V_{se,\,3,\,max}|)}{X_1} \tag{8}$$

It is illustrated that the control boundary of MUPFC can be developed to a form similar to ellipse, as shown in Fig. 13. To reach the same controllability as UPFC, the power rating of MUPFC converters at the reference frequency should be equaled to one UPFC.

Because the current and voltages at the 3th-harmonic component have to be extended, the rating of MUPFC converter is a little larger than UPFC. In this case, the enhanced rating of power is related the active power interchanged at the 3th-harmonic component. In transmission line, the related

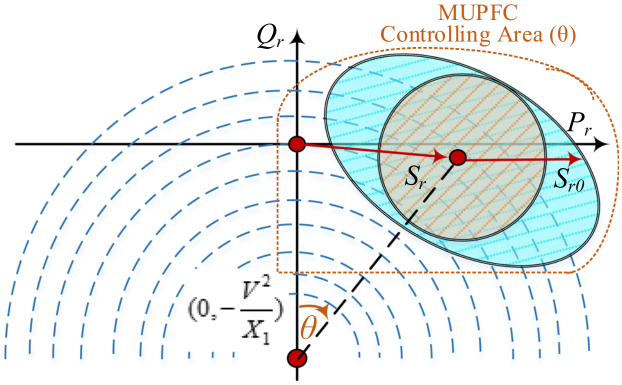

Fig. 13 Power flow controlling range of MUPFC

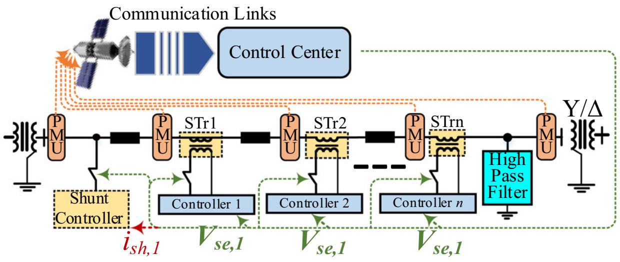

Fig. 14 MUPFC controlling block diagram

impedances $|X_1|$ is usually about 0.05 p.u.. By assuming that the bus voltages $|V|$ and power $|S_{\text{r0}}|$ without acting MUPFC is 1 p.u., from (7), it can be seen that for controlling 1 p.u. power flow in the transmission line, the interchanged active power is about 0.05 p.u.

As a result, it can be seen that with additional current and voltage at the 3th-harmonic component, the cost of MUPFC is still lower than UPFC. It can be due to the following items: (1) the MUPFC converters use low-voltage level (lower than 1 kV), which the devices are much cheaper than the related devices used in UPFC in high voltage level; (2) In the proposed MUPFC, the series converters are floating and therefore no land is required in this structure.

4 MUPFC control

For controlling converters, the proposed MUPFC is developed through three different controllers as (1) central controller, (2) series controller and (3) shunt controller as indicated in Fig. 14. As it is shown, the series and shunt controllers are local and specified for controlling local oscillations, however, central controller provides the concept of distributed MUPFC functions for damping wide area oscillations on power system.

From Fig. 14, three types of controllers have its own functions are as follows.

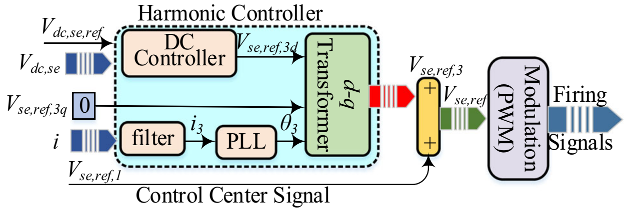

Fig. 15 The structure of the series controller

4.1 Central controller

In central control, the base signals are generated for both series and shunt converters. In fact, central controller provides required damping signals for controlling power flow, low-frequency oscillation and transient stability improvement. During consecutive time windows, the PMU voltage and current phasors are evaluated on control center in which the 1_{th} component of voltage $V_{\text{se},1}$ and current $i_{\text{sh},1}$ signals are provided and sent to series single-phase and shunt converters, respectively.

It is noted that, all of the produced signals by central controller are generated at the reference frequency.

4.2 Series controller

In the proposed scheme, each series converter is equipped with its own controller. The series controller is applied to control the capacitor voltage using 3th-harmonic components. In this case, central controller provides the 1th voltage at reference frequency in which added to the main 3th series signal. Based on Fig. 15, the proposed series controller consists of major controlling blocks including DC controller, PLL and *dq* transformation to provide 3th-harmonic components. Principle of the vector control is applied here for controlling the dc-voltage [10]. Basic structure of the proposed series converter is shown in Fig. 15.

Due to simplifying the capture of PLL [11], the 3th-harmonic current of transmission lines is determined here as the base rotation reference in park transformation applications. Through simulation evaluations, it revealed that the transmission line current has two different frequencies where one 3th-order high-pass filter is required to decrease the reference current.

The *d*-component of the 3th-harmonic voltage is the parameter that applied for controlling dc voltage from which fundamental signal is produced with the dc voltage controlling loop.

In order to decrease the reactive power generated from 3th-harmonic component, controllable resistances connected to the series converters in which tunned at the 3th-harmonic frequency. In this case, the voltage *q*-component is fixed to zero within the operation condition.

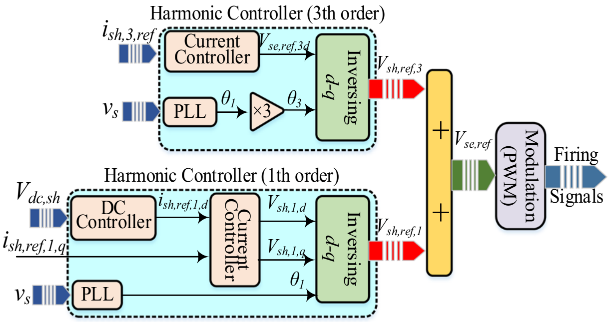

Fig. 16 Block diagram of shunt converter control

Due to single phase connections of series converters, there are voltage ripples at dc sides depends on current frequency within converters. Also, the output current generated from converters consist both reference 1th and 3th orders which resulted in the output dc voltage contain different frequencies like 100, 200 and 300 Hz [12, 13]. To reduce voltage ripples, there are two feasible ways. The first way is to increase the series single-phase transformers turn ratios resulted in decreasing the current magnitude flows within the converters. The second way is to apply a large dc capacitor installed at series converters locations.

4.3 Shunt control

Controlling structure of the proposed shunt converter is shown in Fig. 16 which the main aim is to generate a fix 3th-harmonic current for transmission lines and produce the required active powers of series converters.

As it is illustrated, the 3th current $i_{\text{sh3,ref}}$ is passed through the current controller which the terminal voltage at reference frequency $V_{\text{sh,ref,3}}$ is developed.

Also, in order to extend the voltage frequencies V_{S}, using PLL, the output signal is tripled which considering the same rotation reference developed in *Sect. 4.2*, the 3th-harmonic frequency components are developed. In this case, the reference frequency is concentrated on generating adjustable reactive currents into the network to fix dc voltage on an individual level. The proposed strategy for the reference frequency components consists two cascade controllers in which the input current is controlled into the inner control loop and used to regulate the shunt current at the reference frequency $i_{\text{sh,ref,1}}$. It is worth noting that the current *d*-component is produced on dc controller where central controller is responsible to establish the current *q*-component on fundamental frequency.

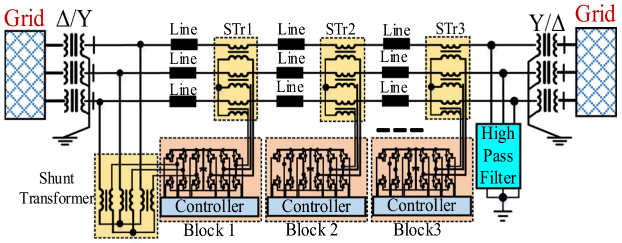

Fig. 17 The related case study with MUPFC

Table 1 Specification of the MUPFC parameters

Symbol	Description	Value	Unit
V_{s}	Nominal voltage of grid s	220	V
V_{r}	Nominal voltage of grid r	220	V
Θ	The angle within grid r and s	1	o
L	The line inductance	6	mH
$V_{\text{sh,max}}$	Maximum voltage of shunt converter	50	V
$I_{\text{sh, max}}$	Maximum current of shunt converter	9	A
$V_{\text{sh, dc}}$	Dc source supply of shunt converter	20	V
$I_{\text{sh,ref,3}}$	The 3*th* current generated by shunt converter	3	A
f_{sw}	Switching frequency for series and shunt converters	6	kHz
$V_{\text{sc, max}}$	Maximum voltage of series converters	7	V
$I_{\text{sc, max}}$	Maximum current of series converters	15	A

5 Simulation results

According to the proposed three controlling approaches, simulation studies of evaluating MUPFC controllers and principles are provided. In this case, considering three-phase transmission line connected between two large power grids showed in Fig. 17, six single-phase series converters and one shunt converter are installed and tested. As it is illustrated, two grid buses are connected using one transmission line which operated through difference operational phase angles.

The shunt converter consists of one single-phase converter and one main neutral to ground connection based transformer.

In the case of developing three developed controllers, the shunt converter are supplied using a fix dc-voltage source with detail parameters illustrated in Table 1.

Also, for series part, considering six series single-phase converters distributed through transmission line, power flows are controlled. In this case, each series controller presents one individual voltage signal $V_{\text{se,ref}}$ passing away through

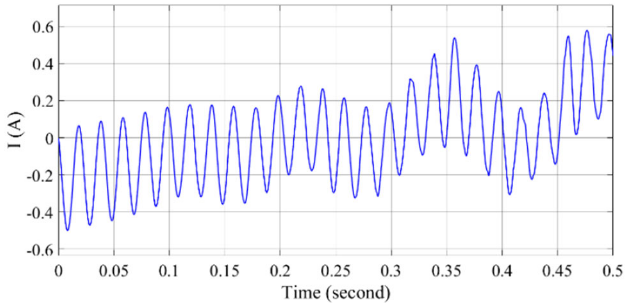

Fig. 18 MUPFC steady state line current

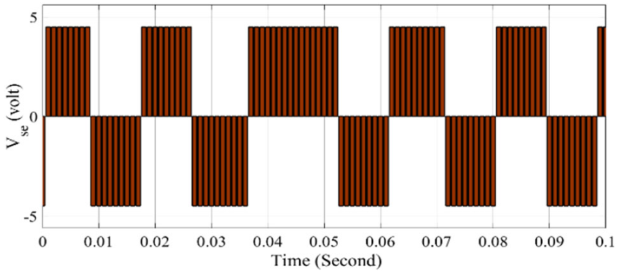

Fig. 19 MUPFC series converter voltage

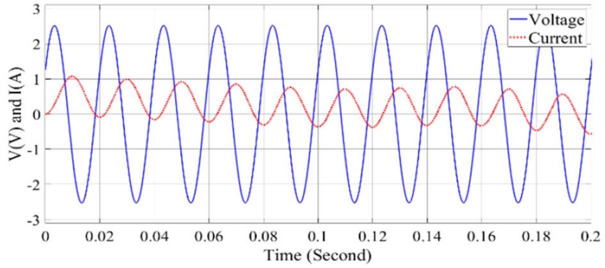

Fig. 20 The bus V and I at Δ side of power transformer

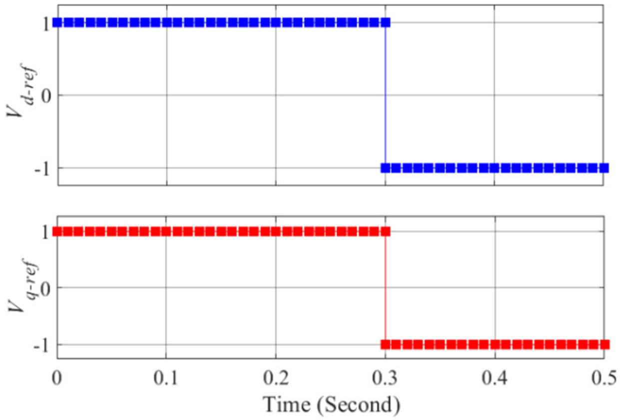

Fig. 21 The step change in fundamental voltage

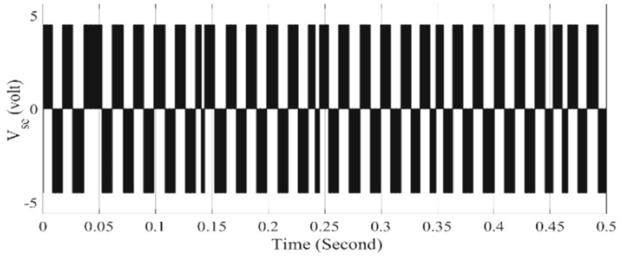

Fig. 22 Series converter voltage of MUPFC according to step change

controller PWM in which proper firing angle with positive effect on damping oscillations are estimated. Using estimated firing angles, MUPFC presents an adaptive damping in phase with the tie-line oscillations in which the line power flow is controlled.

To assess the proposed MUPFC structure, two different scenarios are evaluated. For the first scenario, considering the system steady state operating condition, the MUPFC damping performance with respect to step response is investigated. For this, series single-phase converters are forced to present the voltage d and q values as $V_{\mathrm{se,d,ref}} = 0.3$ V and $V_{\mathrm{se,q,ref}} = -0.1$ V, respectively.

The current within the line, voltage generated by the series converters and the current and voltage at Δ side of the power transformer are indicated in Figs. 18, 19 and 20, respectively. As it is shown in Fig. 18, the fixed 3th-harmonic current component produced by shunt converter is distributed into the three phases which added to reference frequency. Also, from Fig. 19, it is illustrated that the voltage generated by series converters also consists of two different frequency components.

Based on Fig. 19, the magnitude of the pulse width modulated (PWM) waveform indicates the dc voltage that is well remained by the 3*th*-harmonic component in steady state operating condition. As it is illustrated, dc voltage has a weak oscillation which do not has influence on three MUPFC controllers. Figure 20 shows the 3th-harmonic filtered signals by the power transformers. As it is shown, using the high pass filter, there is no 3th-harmonic voltage or current signals at Δ side of power transformer. In this case, MUPFC adjust the power flow within transmission lines by controlling the voltage generated by series single-phase converters at reference frequency.

Also, comparing the Figs. 18 and 20 revealed that, the frequency of simulations in Fig. 18 are three times of waveforms in Fig. 20. It means that, using the proposed distributed controllers, only the 3*th* order harmonic is generated and used as input to series and shunt converters.

In fact, the signals in Fig. 18 is the input of developed filter which Fig. 20 presents the filter output signals. In this case, all 3*th* harmonics are mainly diminished through passing the filter.

Figures 21, 22, 23, 24 and 25 indicate the step response of MUPFC within the simulation results. In the case study, it is

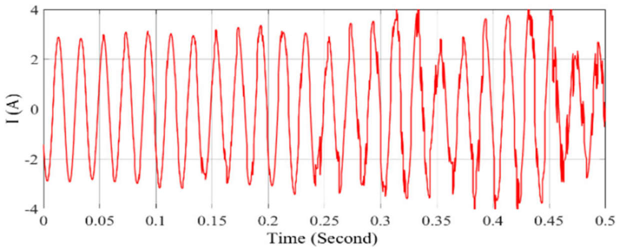

Fig. 23 The line current according to step change

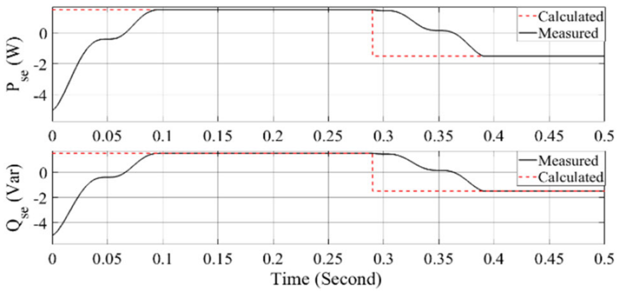

Fig. 24 Powers of series converter at the reference frequency

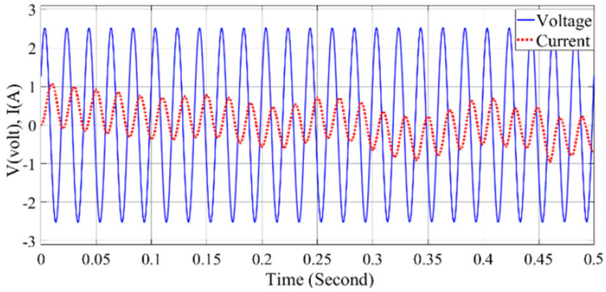

Fig. 25 The current and voltage at the Δ side of power transformer

considered that the series converters made a step change in reference voltage as shown in Fig. 21. This change is caused to variation in both reactive and active powers generated by two converters. As it is shown in Fig. 21, the dc voltage generated by series converters is established after the step change. In order to evaluate the MUPFC controlling performance, the voltage and current of converters during step changes are investigated.

As indicated in Fig. 22, in the case of changing on dc voltage $V_{d\text{-}ref}$ and $V_{q\text{-}ref}$, the voltages of series converters are reversed which present sinusoidal reverse current on transmission line. In fact, the PMU phasors are passed through converter PWM logics in which firing angle signals with the potential of trigging the converter IGBT's are generated. The measured series converter voltage and corresponding line current are shown in Figs. 22 and 23, respectively.

In this case, converter generate/receive the reactive and active power from/to the network at the reference frequency f_1. As it is illustrated in Fig. 24, during step changes-based calculated powers, the reactive and active powers generated by series converters are varies which means the real-time performance of controllers with respect to transmission line operational conditions.

It is illustrated that the series single-phase converters are able to receive and generate both reactive and active power to the network at the reference frequency. The simulation results show the capability of the proposed MUPFC for controlling the both active and reactive powers into the grid. Also, to ensure that the generated 3th-harmonic component is eliminated, the voltage and current in Δ side of power transformer are measured which are shown in Fig. 25. It can be seen that by using Y-Δ connection for the power transformers, the generated 3th-harmonic component is eliminated properly which the output voltage and current contain only fundamental frequency.

It is worth noting that, during the step changes, two reverse values + 1 and − 1 considered for controller real-time evaluations. In this case, during the first part (0–0.3 s), the value of input step source in + 1 where during the next time (0.3–0.5 s) the step changed to − 1 value. Based on the converter voltage and current in Figs. 22 and 23 and corresponding reactive and active powers in Fig. 24, it is revealed that for the first period (0–0.3 s), converter generate the active and reactive power which after just 0.1 s, reached to nominal value. However, for the second period (0.3–0.5 s), by changing the input step, the controllers followed this change which the output powers are reversed consequently. So, at each time window, based on evaluating input response, proper controlling response are developed and observed on converter outputs.

6 Conclusion

This paper presented a modified concept of UPFC called MUPFC for controlling the power flow in transmission lines by distributing series-converter part. The proposed MUPFC structure has been derived from the conventional UPFC which similarly control the bus voltage, angles and the line impedance. In the proposed scheme, the common dc link within the series and shunt converters which is applied for interchanging active power in UPFC has been eliminated and the power has been transmitted within the transmission line at the 3th-harmonic frequency component. In the proposed scheme, the series part of UPFC has been distributed, which several small-size single-phase converters have been proposed instead of one large series converter. By this way, the reliability and security of the proposed MUPFC is considerably increased due to distributing the series converters in transmission lines. Because of the single-phase isolation for each series converter, the overall cost of MUPFC is considerably lower than the UPFC. The proposed scheme has been assessed by considering the related simulation studies in the presence of converter failures. It is demonstrated that the series and shunt converters in the MUPFC can interchange the active power at the 3th-harmonic frequency which the series converters are capable to generate adjustable reactive and active power at the reference frequency.

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Declarations

Conflict of interest The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Also, the research title is originally developed according to today’s power system challenges in the filed of dynamic power system.

Ethical approval Hereby, I Dr.Soheil Ranjbar consciously assure that for the manuscript "Wide Area Voltage Sag Control in Transmission Lines Using Modified UPFC" the following is fulfilled: (1) This material is the authors’ own original work, which has not been previously published elsewhere. (2) The paper is not currently being considered for publication elsewhere. (3) The paper reflects the authors’ own research and analysis in a truthful and complete manner. (4) The paper properly credits the meaningful contributions of co-authors and co-researchers. (5) The results are appropriately placed in the context of prior and existing research. (6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference. (7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content. I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

References

1. Blaabjerg F, Yang Y, Yang D, Wang X (2020) Distributed power-generation systems and protection. Proc IEEE 105(7):1311–1331
2. Chamorro HR, Sevilla FRS, Gonzalez-Longatt F, Rouzbehi K, Chavez H, Sood VK (2020) Innovative primary frequency control in low-inertia power systems based on wide-area RoCoF sharing. IET Energy Syst Integr 2(2):151–160
3. Wang T, O’Neill D, Kamath H (2021) Dynamic control and optimization of distributed energy resources in a microgrid. IEEE Trans Smart Grid 6(6):2884–2894
4. Shuvra MA, Chowdhury B (2019) Distributed dynamic grid support using smart PV inverters during unbalanced grid faults. IET Renew Power Gener 13(4):598–608
5. Huang X, Liu H, Zhang B, Wang J, Xu X (2019) Research on local voltage control strategy based on high-penetration distributed PV systems. J Eng 2019(18):5044–5048
6. Wang R, Sun Q, Liu X, Ma D (2019) Power flow calculation based on local controller impedance features for the AC microgrid with distributed generations. IET Energy Syst Integr 1(3):202–209
7. Hirata K, Akutsu H, Ohori A, Hattori N, Ohta Y (2018) Decentralized voltage regulation for PV generation plants using real-time pricing strategy. IEEE Trans Ind Electron 64(6):5222–5232
8. Zhang B, Lam AYS, Domínguez-García AD, Tse D (2022) An optimal and distributed method for voltage regulation in power distribution systems. IEEE Trans Power Syst 30(4):1714–1726
9. Zhu H, Liu HJ (2020) Fast local voltage control under limited reactive power: optimality and stability analysis. IEEE Trans Power Syst 31(5):3794–3803
10. Wang Z, Wu W, Zhang B (2018) A distributed quasi-Newton method for droop-free primary frequency control in autonomous microgrids. IEEE Trans Smart Grid 9(3):2214–2223
11. Wang Z, Wu W, Zhang B (2016) A fully distributed power dispatch method for fast frequency recovery and minimal generation cost in autonomous microgrids. IEEE Trans Smart Grid 7(1):19–31
12. Wang Z, Wu W, Zhang B (2015) A fully distributed active power control method with minimum generation cost in grid-connected microgrids. In: Proceedings of the IEEE Power and Energy Society General Meeting, pp 1–5
13. Mokhtari A, Ling Q, Ribeiro A (2015) An approximate Newton method for distributed optimization. In: Proceedings of the IEEE international conference on acoustics speech and signal processing, pp 2959–2963