

A Novel Complete Dynamic and Static Model of 48-Pulse VSC-based GUPFC for Parallel Transmission Lines

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A Generalized Unified Power Flow Controller (GUPFC) is a member of the flexible alternating current transmission system
B (FACTS) devices family that operates based on voltage source converter (VSC) and is known as the most efficient FACTS
S device. GUPFC can control the voltage of one bus and the active and reactive power flows on at least two transmission
T lines with equal voltage levels. This paper presents the mathematical modeling of power injection by GUPFC for the first
R time. Besides, the accurate design and details of the control system for series and shunt converters of a GUPFC, along with
A a new mathematical function for pulse generation based on a 48-pulse VSC when the GUPFC is placed in the middle point
C of a parallel transmission line, are presented in this study. The power injection modeling introduced in this paper is very
T useful and efficient in Newton-Raphson power flow studies and in modeling different parts of the control system and power
electronics converter in dynamic and transient studies. The modeling is implemented in MATLAB/Simulink for a 400 km,
230 kV, and 60 Hz nominal frequency double-circuit transmission line. The satisfactory results provided in the simulations
section of the paper verify the validity and accurate performance of the proposed model.

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I. INTRODUCTION

Various solutions have so far been proposed for solving the problems caused by electrical energy transmission. One of the most significant and efficient solutions is the application of FACTS devices. Advances in the manufacturing of power electronics converters with high-speed switching [1] and the improved technology of control processors have led to a dramatic growth of novel ideas in designing FACTS devices [2]. To date, 10 types of compensators from the FACTS family have virtually been introduced in terms of theory as well as the experimental and practical manufacturing processes [3]. In 2000, Fardanesh et al. introduced, for the first time, a new concept of the most complete and advanced type of multi-converter FACTS, called GUPFC. Fig. 1 shows the various topologies of GUPFC in the power system. Generally speaking, this device consists of n ($n \geq 2$) series and shunt converters [4].

Once the GUPFC was introduced, similar FACTS devices including GIPFC and MUPFC were also presented [5-6]. These devices have two major common features. First, they can be placed on more than one single transmission line; second, regarding their special topology, each of them contains both series and shunt converters. The main difference between GUPFC and GIPFC is that GUPFC can be used on at least two parallel transmission lines with the same voltage level. However, GIPFC is placed on at least two transmission lines with different voltage levels. The major difference between GUPFC and MUPFC is in the number of shunt converters. GUPFC has only one shunt converter while the number of shunt converters in MUPFC is equal to the number of its series converters. Furthermore, MUPFC can be employed in transmission lines with equal or different voltage levels. After the publication of the first paper in the field of GUPFC, building and installing a GUPFC device was practically proposed in Xinjiang, China, due to several reasons including numerous problems in power transmission to long distances,

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huge economic loss, and inappropriate power flow distribution which posed a risk to the system safety [7].

Basically, we can classify the literature on GUPFC into several main categories. A number of papers associated with GUPFC have focused specifically on the GUPFC modeling problem in the realm of power flow studies [8-14]. The mathematical modeling of GUPFC using the rating method, and a specific device for Newton-Raphson power flow studies have been presented for power systems [8]. The GUPFC modeling is discussed in the optimal power flow in the nonlinear internal point [9]. The authors in [10] provide the results obtained from utilizing GUPFC in a 28-bus, 330 kV in Nigeria for optimal power flow and voltage drop reduction. Ref. [11] argues the optimal location of GUPFC, the optimal power flow, and the modification of the Jacobian matrix in the presence of GUPFC. The developed model of GUPFC in the analysis of the Newton-Raphson power flow is given in [12] using the combined non-conformity method. Also, the development of GUPFC in Newton-Raphson method without modifying the Jacobian matrix and considering the power flow constraints is discussed in [13]. In another study, an impedance compensation method is used to solve numerical instability problems of power flow analysis in power systems equipped with the GUPFC [14].

The second category includes the dynamic studies and the analysis of various types of stabilities in the presence of GUPFC [15-20]. A control algorithm based on a fuzzy-neural network controller is presented in [15] to improve transient stability. A new algorithm for calculating the power quality index under steady-state and transient conditions is introduced in [16] using the harmonics technique in the presence of GUPFC. To study small-signal stability, a dynamic modeling based on the Heffron-Phillips model of a power system equipped with a GUPFC along with a PSS is proposed in [17]. An algorithm for enhancing the performance of GUPFC using a fuzzy logic-based controller is presented in [18]. Ref. [19] deals with the effect of GUPFC on small-signal stability of power systems. Also, the authors in [20] discuss the sub-synchronous resonance phenomenon in transmission lines compensated by GUPFC.

Still another group of studies concentrate on the operation and economic analyses of the presence of GUPFC in power systems [21-26]. A sensitivity-based approach for deciding on the proper location of GUPFC to perform an optimal power flow and its effect on power generation and transmission costs is suggested in [21]. Furthermore, a novel optimization algorithm for solving the economic problem of emissions and loss reduction in a power system equipped with GUPFC is presented in [22]. A new optimization method based on the PSO algorithm is given in [23] to optimize the generation cost objectives subject to various practical constraints in a power system equipped with GUPFC. The authors in [24] use a nonlinear internal point optimization method to calculate the

transmission capability of a power system equipped with GUPFC. The increase in the loading capability of power system through the optimal placement of GUPFC based on PSO is presented in [25]. Line congestion management algorithm based on demand management for a combination of bilateral pool electricity market in a power system equipped with GUPFC is suggested in [26].

A different body of research deals with power quality assessment in power systems with GUPFC [27-28]. Ref. [27] studies the effect of GUPFC on the improvement of power quality and the total harmonic distortion (THD) level. Also, the concept of using GUPFC for reducing voltage flicker phenomenon and improving power quality is proposed in [28]. Finally, in the last group, Ref. [29] analyzes the positive effects of GUPFC on the distance relaying operation in transmission lines.

A thorough scrutiny of the literature shows that all power flow modeling studies performed in the presence of GUPFC for models given in Figs. 1 (a) and (b). Moreover, a major part of literature deals with the impact of GUPFC on power systems and discusses the accurate modeling of different control parts while related power electronics have rarely been investigated.

The topology given in Fig. 1(a) is used when the goal is to control the near-end bus voltage of the double-circuit line and to control power at a double-circuit line with distinctive remote-end buses with different voltages. The two circuits in the topology may differ in terms of distance. The topology given in Fig. 1(b) is employed when the goal is to regulate the near-end bus voltage and control power on one of the double-circuit lines with a common remote-end bus. The distances of both circuits in this topology are equal. The topology given in Fig. 1(c) is utilized when the aim is to regulate voltage along the path on the double-circuit line, especially in the middle of the line. The near and remote-end buses of both circuits in this topology are the same. According to the mentioned differences in different topologies provided in Fig. 1, the GUPFC modeling is different in Newton-Raphson power flow equations and in building the Jacobian matrix. Furthermore, control parameters in the series and shunt converters of the GUPFC in different topologies given in Fig. 1 are different because of power system stabilization in the presence of GUPFC, satisfying different constraints of power flow, and bus voltage control.

The main contributions of the present study are: 1) the accurate mathematical modeling of active and reactive power injections by GUPFC based on the topology given in Fig. 1 (c), which is exclusive for Newton-Raphson power flow studies, 2) the accurate modeling of different parts of the control system of the 48-pulse VSC-based GUPFC, and 3) the presentation of a new mathematical function to generate a 48-pulse signal required in the GUPFC, instead of using the classic 48-pulse signal generator system. The logic used in this block generates the firing angle signals of the 48-pulse VSC's gate turn-off

thyristor (GTO).

Using harmonic filters along with FACTS devices to remove harmonics produced by voltage source inverters embedded within the filters leads to increased installation and operation costs of FACTS devices in the power system. Hence, to solve the power quality problem and reduce the harmonic distortions level in output voltage of the converters used in the FACTS devices, the paper presents 48-pulse voltage source inverters. The application of 48-pulse converters within the GUPFC helps reduce the harmonic level of the output voltage so that there is no need to use harmonic elimination filters, making it really cost-effective.

The paper is organized as follows. The mathematical modeling of the active and reactive power injection by the GUPFC is presented in Section 2 of the paper, which is exclusive to Newton-Raphson power flow studies. Section 3 describes the accurate design of the GUPFC's controller system. Section 4 discusses the inverter modeling of the 48-pulse VSC-based GUPFC using a new mathematical function for the pulse generator. Software simulations and the obtained results are provided in Section 5. Section 6 presents conclusions, and finally, the Appendixes include the test system data.

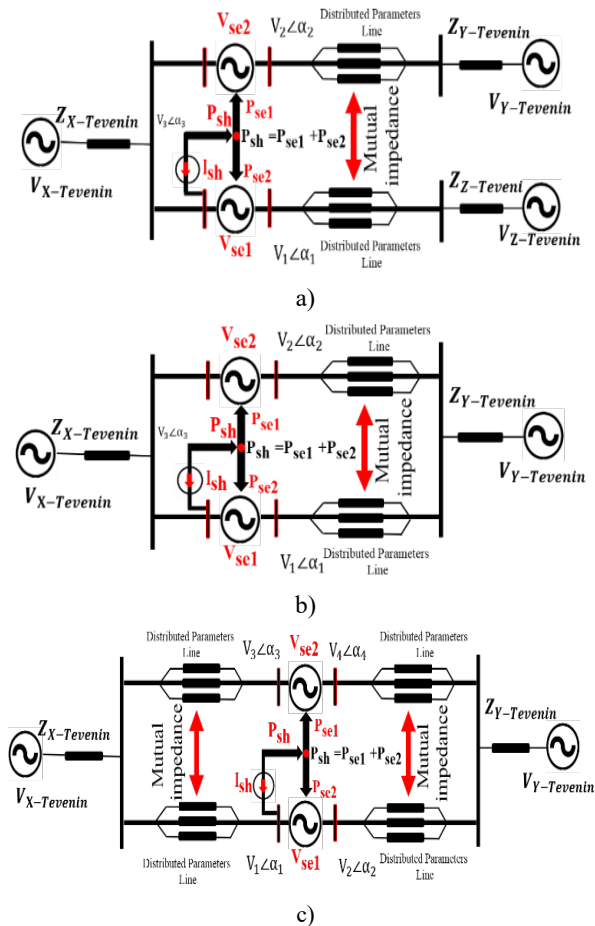


Fig. 1. Various topologies of GUPFC [9,17,29].

II. MATHEMATICAL MODELING OF ACTIVE AND REACTIVE POWER INJECTIONS BY THE GUPFC

For mathematical modeling of the power equations of GUPFC, Thevenin and Norton equivalent circuits are used. Fig. 2 shows such circuits for a GUPFC installed on a double-circuit line.

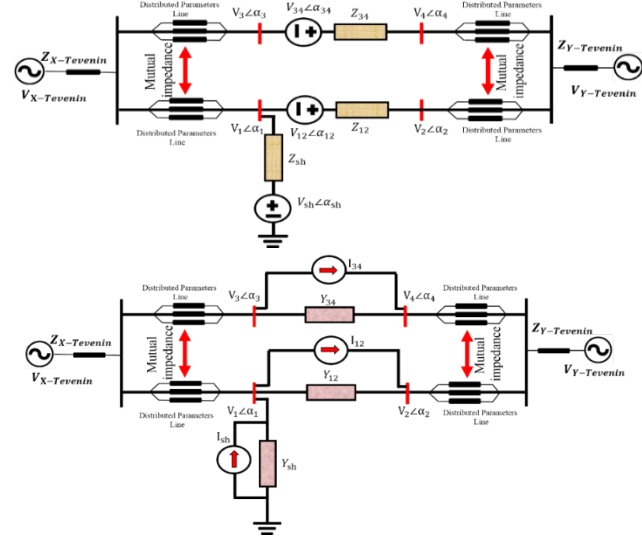


Fig. 2. (a) Thevenin equivalent circuit of a GUPFC, (b) Norton equivalent circuit of a GUPFC.

First, the current of the Norton equivalent circuit of GUPFC is calculated for the two series converters:

$$\vec{I}_{12} = \frac{\vec{V}_{12}}{Z_{12}} = \frac{\vec{V}_{12}}{R_{12} + jX_{12}} = \frac{V_{12}}{\sqrt{R_{12}^2 + X_{12}^2}} \angle \alpha_{12} - \tan^{-1}\left(\frac{X_{12}}{R_{12}}\right) \quad (1)$$

$$\vec{I}_{34} = \frac{\vec{V}_{34}}{Z_{34}} = \frac{\vec{V}_{34}}{R_{34} + jX_{34}} = \frac{V_{34}}{\sqrt{R_{34}^2 + X_{34}^2}} \angle \alpha_{34} - \tan^{-1}\left(\frac{X_{34}}{R_{34}}\right) \quad (2)$$

In the remaining, using the currents calculated in (1) and (2), we can find complex powers of buses based on power injection by series converters:

$$S_1 = \vec{V}_1 (-\vec{I}_{12})^* \quad (3)$$

$$S_2 = \vec{V}_2 (\vec{I}_{12})^* \quad (4)$$

$$S_3 = \vec{V}_3 (-\vec{I}_{34})^* \quad (5)$$

$$S_4 = \vec{V}_4 (\vec{I}_{34})^* \quad (6)$$

Replacing (1) in (3) and (4) and substituting (2) in (5) and (6) help separate (3) and (4) and express them in the form of active and reactive power equations as given in (7) to (10).

$$P_1 = \frac{V_1 V_{12}}{|Z_{12}|^2} (X_{12} \sin(\alpha_1 - \alpha_{12}) - R_{12} \sin(\alpha_1 - \alpha_{12})) \quad (7-a)$$

$$Q_1 = -\frac{V_1 V_{12}}{|Z_{12}|^2} (X_{12} \cos(\alpha_1 - \alpha_{12}) + R_{12} \sin(\alpha_1 - \alpha_{12})) \quad (7-b)$$

$$P_2 = \frac{V_2 V_{12}}{|Z_{12}|^2} (-X_{12} \sin(\alpha_2 - \alpha_{12}) + R_{12} \sin(\alpha_2 - \alpha_{12})) \quad (8-a)$$

$$Q_2 = \frac{V_2 V_{12}}{|Z_{12}|^2} (X_{12} \cos(\alpha_2 - \alpha_{12}) + R_{12} \sin(\alpha_2 - \alpha_{12})) \quad (8-b)$$

$$P_3 = \frac{V_3 V_{34}}{|Z_{34}|^2} (X_{34} \sin(\alpha_3 - \alpha_{34}) - R_{34} \sin(\alpha_3 - \alpha_{34})) \quad (9-a)$$

$$Q_3 = -\frac{V_3 V_{34}}{|Z_{34}|^2} (X_{34} \cos(\alpha_3 - \alpha_{34}) + R_{34} \sin(\alpha_3 - \alpha_{34})) \quad (9-b)$$

$$P_4 = \frac{V_4 V_{34}}{|Z_{34}|^2} (-X_{34} \sin(\alpha_4 - \alpha_{34}) + R_{34} \sin(\alpha_4 - \alpha_{34})) \quad (10-a)$$

$$Q_4 = \frac{V_4 V_{34}}{|Z_{34}|^2} (X_{34} \cos(\alpha_4 - \alpha_{34}) + R_{34} \sin(\alpha_4 - \alpha_{34})) \quad (10-b)$$

In addition, the complex power lost in Z_{12} and Z_{34} is defined according to (11).

$$S_{imp12} = \vec{V}_{12}(\vec{I}_{12})^* = \frac{V_{12}^2}{|Z_{12}|^2}(R_{12} + jX_{12}) \quad (11-a)$$

$$S_{imp34} = \vec{V}_{34}(\vec{I}_{34})^* = \frac{V_{34}^2}{|Z_{34}|^2}(R_{34} + jX_{34}) \quad (11-b)$$

The exchanged active power of the shunt compensator is calculated in Eq. (12) with regard to the active power balance condition of the GUPFC:

$$P_{sh} = -(P_{12} + P_{34}) \quad (12)$$

where P_{12} and P_{34} are found from (13-a) and (13-b):

$$P_{12} = P_1 + P_2 - \frac{V_{12}^2}{|Z_{12}|^2} R_{12} \quad (13-a)$$

$$P_{34} = P_3 + P_4 - \frac{V_{34}^2}{|Z_{34}|^2} R_{34} \quad (13-b)$$

Moreover, to calculate reactive power of the shunt converter, the same calculations as used for finding reactive power of the series converter is utilized in this step. Finally, (14) helps obtain the reactive power of the shunt converter.

$$Q_{sh} = \frac{V_1 V_{sh}}{|Z_{sh}|^2} (X_{sh} \cos(\alpha_1 - \alpha_{sh}) + R_{sh} \sin(\alpha_1 - \alpha_{sh})) \quad (14)$$

The complex powers injected to buses 1 to 4 are calculated using (15) to (18).

$$S_{1,GUPFC} = P_{1,GUPFC} + jQ_{1,GUPFC} = (P_1 + P_{sh}) + j(Q_1 + Q_{sh}) \quad (15)$$

$$S_{2,GUPFC} = P_{2,GUPFC} + jQ_{2,GUPFC} = P_2 + jQ_2 \quad (16)$$

$$S_{3,GUPFC} = P_{3,GUPFC} + jQ_{3,GUPFC} = P_3 + jQ_3 \quad (17)$$

$$S_{4,GUPFC} = P_{4,GUPFC} + jQ_{4,GUPFC} = P_4 + jQ_4 \quad (18)$$

As a result, the equivalent circuit of the double-circuit line compensated by GUPFC is represented in terms of complex powers injected to buses 1 to 4, as shown in Fig. 3.

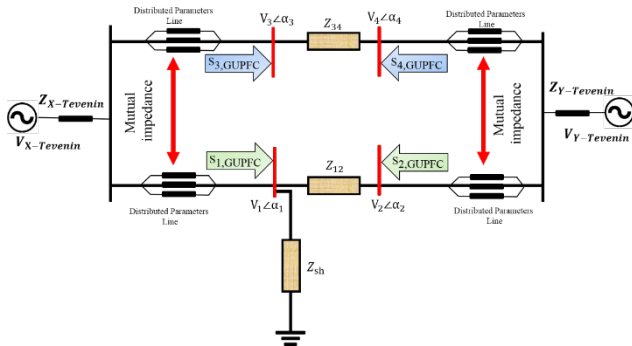


Fig. 3. Equivalent circuit of the double-circuit line compensated by GUPFC in terms of the injected complex power.

Once the steady-state model of GUPFC shown in Fig. 3 is extracted, a modification is applied to the Jacobian matrix and Newton-Raphson power flow equations based on the extracted model and power flow studies are carried out regarding the new model.

III. ACCURATE DESIGN OF THE GUPFC'S CONTROLLER SYSTEM

Referring to Fig. 4, the shunt converter controls the voltage of bus 1. This is performed through exchanging reactive power with the grid, i.e. via controlling the voltage of the DC-link. To realize this, at first, the proper angle ωt for synchronization of voltage and current is calculated using a phase-locked loop (PLL). Then, using the abc-dq0 transform, the three-phase

voltage and current components fed to the shunt converter are transformed into active and reactive components. Next, the measured voltage of the bus connected to the shunt converter is instantaneously compared with the reference voltage and is injected to the PI controller so that the error signal is calculated to generate the reference reactive current. In the next step, a comparison is made between the reference reactive current calculated in the previous step and the reactive power of the shunt converter-connected bus. The difference between these two quantities is used as the input in the proportional-integral (PI) controller to generate the phase angle alpha of the inverter voltage. D-alpha is another component used in this converter which is generated by applying the average DC-link voltage values and the reactive power to the PI controller. The last component required for pulse generation by the firing pulse generation system is sigma. Put differently, Sigma is the same modulation index that impacts the amplitude of the converter's output voltage and its value is 172.5. Based on Fig. 1 (c), a GUPFC has two series converters with similar control systems. In this section, we investigate only one series converter knowing that the second one is identical. As per Fig. 5, the series converter is employed to automatically control power flow and adjust the current flowing from the transmission line. In this converter, similar to the shunt converter, the three-phase voltage measured from the bus is connected to one side of the series converter and the PLL calculates the proper angle, ωt , to synchronize voltage and current components. Then, the active and reactive components related to three-phase currents and voltages of the buses are calculated using the abc-dq0 transform. According to Fig. 5, the reference active and reactive currents can be found using the reference active power, the reference reactive power, the active voltage, and the reactive voltage. The calculated reference active and reactive currents are compared with their counterparts from the bus. After that, the error signal is fed to the proportional-integral-differential (PID) controller to calculate the reference active and reactive voltages. Next, a limiter controls the reference active and reactive voltages to prevent any possible system instability. Finally, the output of the real and imaginary voltage limiters is employed for calculating Alpha and Sigma. As the value of D_Alpha is obtained from the shunt converter, it is set zero in this section of the paper.

Coefficients k_i and k_p used in the series and shunt controllers of the GUPFC are calculated first by using the closed-loop Ziegler-Nichols method and then by trial and error to stabilize the test power system, achieve the balance among constraints, reach ideal operation conditions, and achieve power and power quality control.

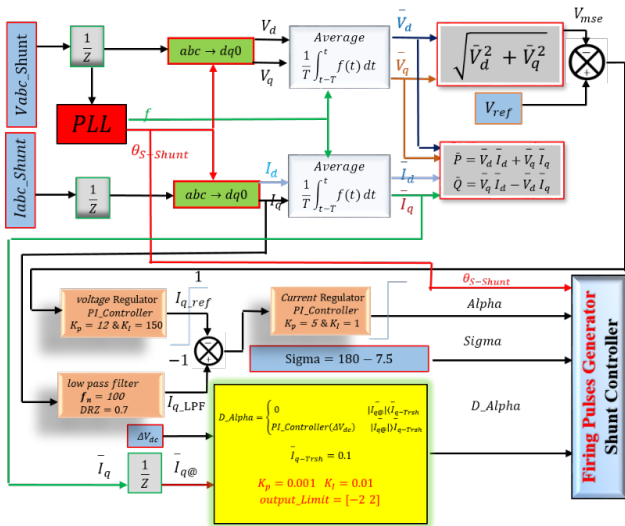


Fig. 4. Control system of the GUPFC's shunt converter.

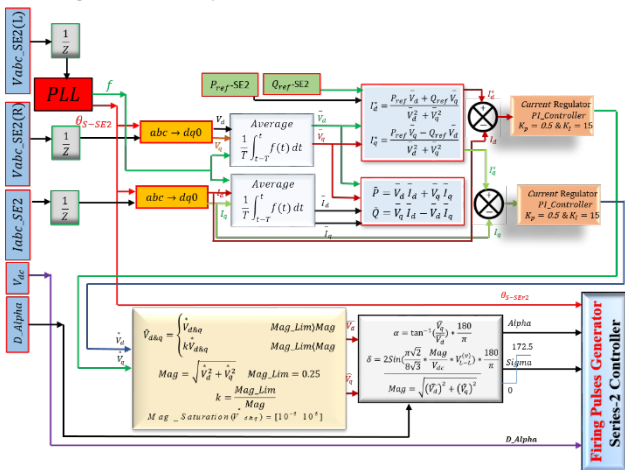


Fig. 5. Control system of the GUPFC's series converter.

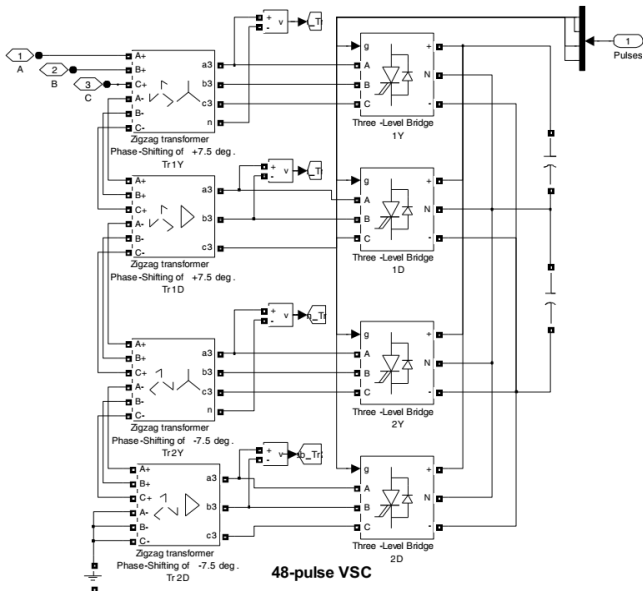


Fig. 6. Model of the GUPFC's voltage source inverter for the shunt converter.

IV. MODELING OF THE 48-PULSE VSC-BASED GUPFC'S INVERTER

Fig. 6 illustrates the inverter system considered for this compensator, which is a 48-pulse GTO voltage source converter and includes four three-level inverters and four phase-shifting transformers. All inverters considered for this converter can generate a three-phase square semi-sine voltage waveform using the three-level GTO bridge inverter. The secondary winding of the phase-shifting transformer uses three phase sequences of the series voltage wave series with the primary winding to generate a virtually sine voltage waveform. The amplitude of the voltage waveform can adopt one of these values: the DC-link voltage, the minus value of the DC-link voltage, or zero. Period of the zero voltage at each quarter-cycle can be defined as a dead-time with a value between 0 to 90°.

A. Analysis of 48-pulse VSC inverters

Two 24-pulse converters with a 7.5° phase shift with respect to each other form a 48-pulse converter. Using symmetry, a -3.75° phase-shift on the transformer connections of one of the 24-pulse converters and a $+3.75^\circ$ phase-shift on the other transformer create the required 7.5° phase-shift. Hence, the firing pulse needs $+3.75^\circ$ and -3.75° phase-shifts, respectively. Four 12-pulse converters that are interconnected using four 12-pulse transformers with phase-shifting windings are used to form a 48-pulse converter. Thanks to its perfect performance and low harmonic rate on the AC side, this converter, needless of AC filters, can be used for applications that demand high power. The output voltage contains harmonic orders of $n = 48r \pm 1$, where $r = 0, 1, 2, \dots$, meaning that harmonics of orders 47^{th} , 49^{th} , 95^{th} , 97^{th} , ... have amplitudes of 0.47, 0.49, 0.95, ... per unit on the base of the fundamental component. Also on the DC side, the lower flowing harmonic current will be considered as the 48^{th} order harmonic component. The phase-shifting pattern for individual 12-pulse converters will be as follows [30]:

- Analysis of the first converter

The output voltage produced by the first converter is:

$$v_{ab12}(t)_1 = 2[V_{ab1} \sin(\omega t + 30^\circ) + V_{ab11} \sin(11\omega t + 195^\circ) + V_{ab13} \sin(13\omega t + 255^\circ) + V_{ab23} \sin(23\omega t + 60^\circ) + V_{ab25} \sin(25\omega t + 120^\circ) + \dots] \quad (19)$$

- Analysis of the second converter

The output voltage produced by the second converter is:

$$v_{ab_{12}}(t)_2 = 2[V_{ab_1} \sin(\omega t + 30^\circ) + V_{ab_{11}} \sin(11\omega t + 15^\circ) + V_{ab_{13}} \sin(13\omega t + 75^\circ) + V_{ab_{23}} \sin(23\omega t + 60^\circ) + V_{ab_{25}} \sin(25\omega t + 120^\circ) + \dots] \quad (20)$$

- Analysis of the third converter

The output voltage produced by the third converter is:

$$v_{ab_{12}}(t)_3 = 2[V_{ab_1} \sin(\omega t + 30^\circ) + V_{ab_{11}} \sin(11\omega t + 285^\circ) + V_{ab_{13}} \sin(13\omega t + 345^\circ) + V_{ab_{23}} \sin(23\omega t + 240^\circ) +$$

$$V_{ab25} \sin(25\omega t + 300^\circ) + \dots] \quad (21)$$

- Analysis of the fourth converter

The output voltage produced by the fourth converter is:

$$v_{ab12}(t)_4 = 2[V_{ab1} \sin(\omega t + 30^\circ) + V_{ab11} \sin(11\omega t + 105^\circ) + V_{ab13} \sin(13\omega t + 165^\circ) + V_{ab23} \sin(23\omega t + 240^\circ) + V_{ab25} \sin(25\omega t + 300^\circ) + \dots] \quad (22)$$

These four AC output voltages, given by (19) to (22), are added to the series connection of secondary windings of the transformers. The following expresses the 48-pulse output AC voltage:

$$v_{ab48}(t) = v_{ab12}(t)_1 + v_{ab12}(t)_2 + v_{ab12}(t)_3 + v_{ab12}(t)_4 \quad (23)$$

$$v_{ab48}(t) = 8[V_{ab1} \sin(\omega t + 30^\circ) + V_{ab47} \sin(47\omega t + 150^\circ) + V_{ab49} \sin(49\omega t + 210^\circ) + V_{ab95} \sin(95\omega t + 330^\circ) + V_{ab97} \sin(97\omega t + 30^\circ) + \dots] \quad (24)$$

The general representation for the 12-pulse AC output voltage is:

$$v_{ab12}(t) = 2 \sum_{n=1}^{\infty} V_{abn} \sin(n\omega t + 30^\circ n) \quad \forall n = 12r \pm 1, r = 0, 1, 2, \dots \quad (25)$$

Applying an 11.25° phase-shift to (25) using a PST:

$$v_{ab12}(t) = 2 \sum_{n=1}^{\infty} V_{abn} \sin(n\omega t + 30^\circ n + 11/25^\circ i) \quad \forall n = 12r \pm 1, r = 0, 1, 2, \dots \quad (26)$$

In the above equation, $i = 1$ for the positive-sequence harmonics is the *abc* sequence and $i = -1$ for negative-sequence harmonics is the *cba* sequence. The line-to-neutral voltage of phase *a* is as follows.

Now, by lagging the firing pulse by 11.25°, we have:

$$v_{ab12}(t) = 2 \sum_{n=1}^{\infty} V_{abn} \sin(n\omega t + 18/75^\circ n + 11/25^\circ i) \quad \forall n = 12r \pm 1, r = 0, 1, 2, \dots \quad (27)$$

As a result, the general term for the line-to-line voltage of a 48-pulse converter is given by (28):

$$v_{ab48}(t) = 8 \sum_{n=1}^{\infty} V_{abn} \sin(n\omega t + 18/75^\circ n + 11/25^\circ i) \quad \forall n = 48r \pm 1, r = 0, 1, 2, \dots \quad (28)$$

The line-to-neutral voltage is:

$$v_{an48}(t) = \frac{8}{\sqrt{3}} [V_{ab1} \sin(\omega t) - V_{ab47} \sin(47\omega t) - V_{ab49} \sin(49\omega t) + V_{ab95} \sin(95\omega t) + V_{ab97} \sin(97\omega t) + \dots] \quad (29)$$

Rewriting (29) gives:

$$v_{an48}(t) = \frac{8}{\sqrt{3}} \sum_{n=1}^{\infty} V_{abn} \sin(n\omega t + 18/75^\circ n - 18/75^\circ i) \quad \forall n = 48r \pm 1, r = 0, 1, 2, \dots \quad (30)$$

Voltages $v_{cn48}(t)$, $v_{bn48}(t)$ have similar patterns except with 120° and 240° phase-shift with respect to $v_{an48}(t)$.

B. Modeling the 48-pulse generator mathematical function

Various methods have so far been introduced for modulations in the power electronics industry, the most popular one of which is pulse width modulation (PWM). PWM methods are characterized by fixed-amplitude pulses where the pulse widths are modulated for controlling the modulator output voltage and reducing its harmonic content. Different

methods of PWM include single-pulse modulation, multi-pulse modulation, and sine modulation, each of which differs from others in terms of the harmonic content in the output voltage. For PWM implementation, a digital IC such as a microcontroller or timer 555 can be used. The generated signal is a train of pulses forming a square waveform. In the related literature, various schemes have been introduced for the design of PWM's switching algorithm. The most well-known scheme is a design that compares wave and triangular waveforms. Fig. 7 shows a new mathematical function for describing pulse generation operations in a 48-pulse VSC. There are four switches at each leg of the inverter, with an overall number of 12 switches embedded for each inverter.

As mentioned in the control system design of the GUPFC, the inputs to the pulse generator function are δ , D_Alpha , $Alpha$, and $\omega t = \theta$. Function *mod* is used with angular values of 2π and β for pulse generation. Angle β is influenced by half of the switch-off duration of switch Q1 in the half cycle $((\pi - \delta)/2)$, D_Alpha , $\omega t = \theta$, and the angle of the beginning of each half-cycle, which can be zero or π . Then the output of the *mod* function is fed to the step function with a magnitude of one, the output of which is zero or one. Next, the values produced by step functions are sent as switching signals of GTOs. Finally, the operation of the two sets of switches (Q1 and Q3) and (Q2 and Q4) at each leg reverse each other. In this modeling, with no need for complex comparators of various waveforms and complicated pulse generation hardware and using only one simple mathematical function, the signals required for switching GTOs on and off are generated.

V. SOFTWARE SIMULATIONS AND RESULTS

Fig. 1 (c) provides the system under study in this paper. The system consists of one coupled double-circuit line with characteristics of 400 km, 230 kV, and 60 Hz representing the distributed model. Both ends of the system are modeled using a Thevenin equivalent circuit. The Appendix provides the detailed data related to the simulated system. The GUPFC employed in this study is placed in the middle of the coupled double-circuit line and its main task is to control active and reactive power flows between the two lines. The shunt converter considered for the GUPFC has a rated power of 200 MVA so that it can supply the power required by each series converter up to 100 MVA.

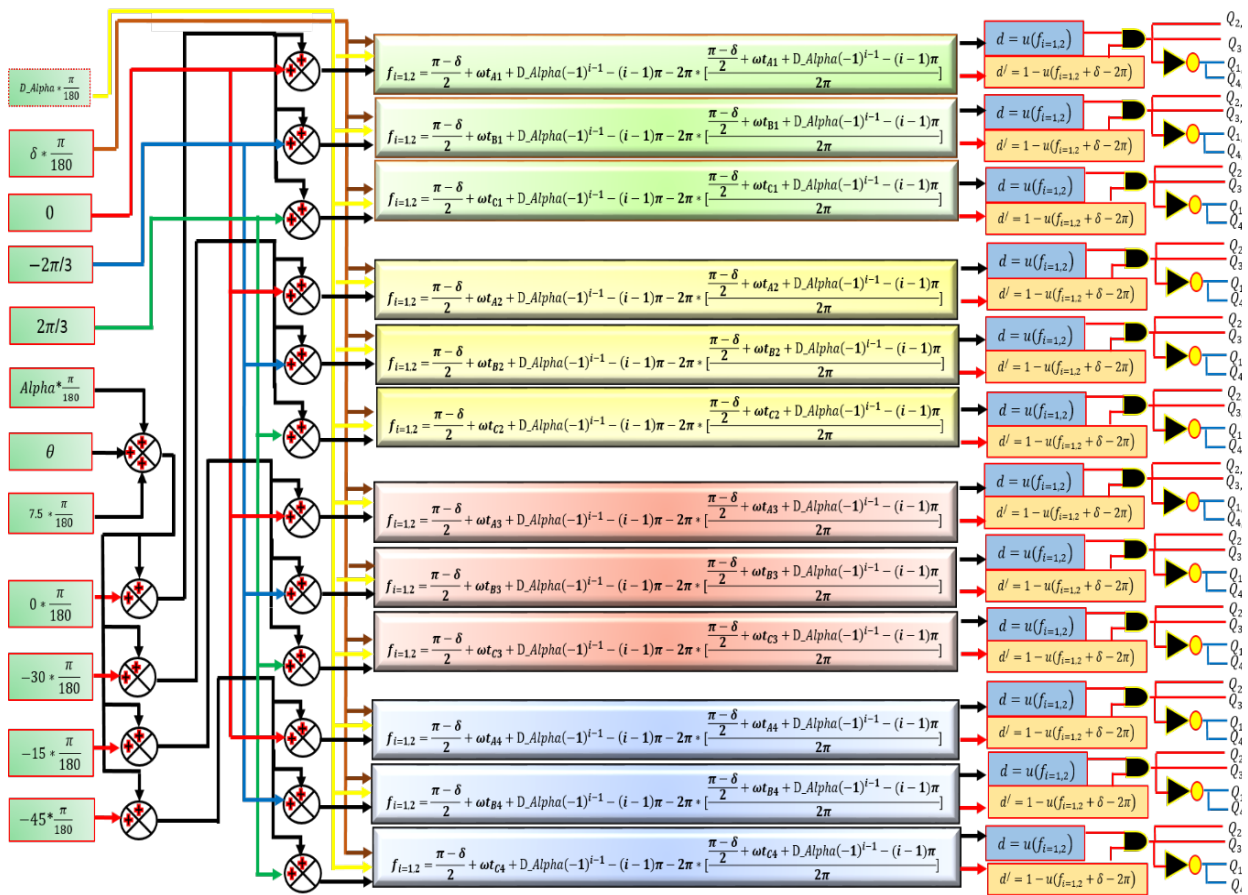


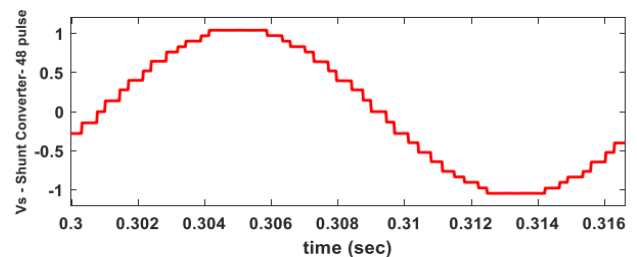
Fig. 7. New mathematical function for generating 48 pulses.

A. Simulation results for the output of the GUPFC's shunt converter

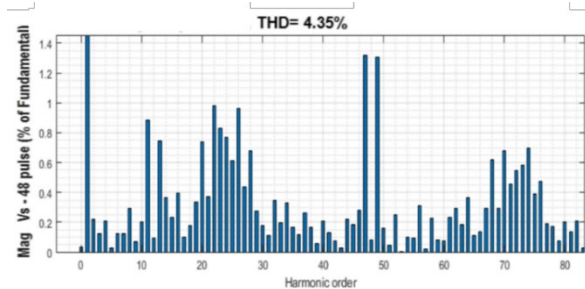
Fig. 8 (a) illustrates the diagram of phase A's secondary voltage for a shunt converter during one cycle. As is seen, the output voltage is a pure 48-pulse signal. Also, Fig. 8 (b) shows the FFT diagram of the output voltage and its THD value (= 4.35%). As expected, the values of the 47th and 49th harmonics are the greatest after the fundamental harmonic value.

Moreover, Fig. 9 shows the voltage of the secondary side and voltage and current of the primary side of the transformer connected to the shunt converter.

Fig. 10 illustrates the active and reactive powers measured at the shunt converter bus. The depicted powers in these diagrams are calculated using three-phase currents and voltages measured from the bus connected to the shunt converter. As is clear, the active and reactive power exchanges between the shunt converter and the grid are positive and negative, respectively. This means that the shunt converter receives active power from the grid to supply the internal loss power and charge the DC-link capacitor, and injects reactive power to the line to maintain the voltage of the bus connected to the shunt converter.



(a)



(b)

Fig. 8 .a) The output voltage of the 48-pulse VSC-based inverter for the parallel converter within a single periodic cycle
b) Harmonic analysis diagram of the output voltage of the 48-pulse VSC-based inverter for the parallel converter within a

single periodic cycle.

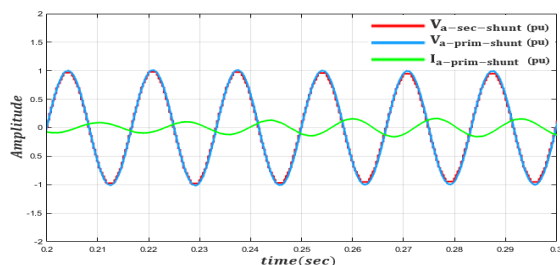


Fig. 9. The voltage of the secondary side and voltage and current of the primary side of the transformer connected to the shunt converter.

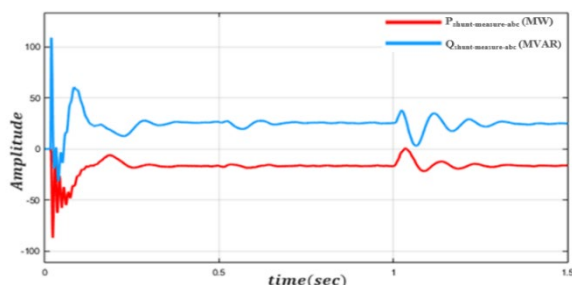


Fig. 10. The active and reactive power diagram for the shunt converter.

Fig. 11 shows the voltage of the bus connected to the shunt converter. Based on the control constraints of the GUPFC, a task of GUPFC is to control the voltage of the bus. In other words, the shunt converter controls the voltage of the middle point of the line. As from Fig. 11 illustrates, the shunt converter suitably maintains the voltage of the middle point of the line close to the reference voltage.

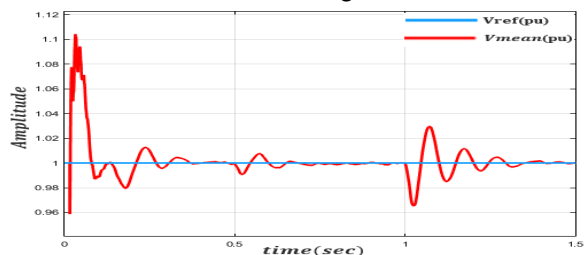


Fig. 11. Diagram of the voltage of the bus connected to the shunt converter.

As is observed in Figs. 10 and 11, an oscillation is seen in the active and reactive power and shunt converter bus voltage 1 s after the start of the simulation. The reason behind this is the great variations in the value of the reference active power at both series converters (converter 1 and converter 2). This change in the power for series converter 1 from a value of 1 to 1.2 and for series converter 2 from 0.9 to -1.2 within 1 s causes changes in the operating mode of the GUPFC besides creating oscillation and transients in the active and reactive powers and voltage of the shunt converter because of satisfying power flow and voltage balance constraints. The established transient and oscillatory state, when the operating mode of the GUPFC changes is utmost two cycles, as shown in Figs. 10 and 11. It

is rapidly damped and the system returns to the steady state.

Fig. 12 presents the voltage of the DC-link connected to three converters. As is observed, the voltage magnitude is maintained almost fixed. As discussed in the section related to the design of the control system, the main aim of controlling D_Alpha is to adjust and balance the capacitor voltages of the DC-link common among all converters. According to Fig. 12, the control of D_Alpha in the control system is performed acceptably.

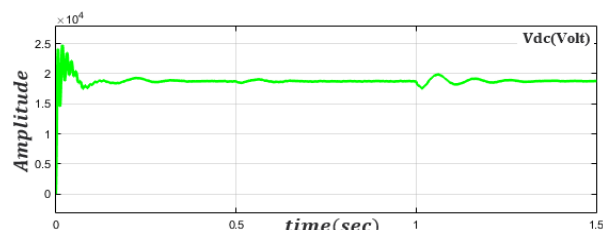


Fig. 12. Voltage of the DC-link common among GUPFC's converters.

B. Simulation results for the output of the GUPFC's series converter 1

Figs. 13 and 14 present the results of active and reactive powers calculated by the control system and the dq reference frame for series converter 1. In these diagrams, active and reactive powers are calculated using the block diagrams provided in Fig. 5.

It is clearly seen that the values of reference active power for the series converter 1 during the time intervals of 0-0.5 s, 0.5-1 s, and 1-1.5 s are 1 p.u., 1.1 p.u., and 1.2 p.u., respectively. Additionally, the reference reactive power for the series converter 1 during the whole period is considered -0.3 p.u. As seen in Figs. 13 and 14, series converter 1 is successful in controlling the active and reactive powers.

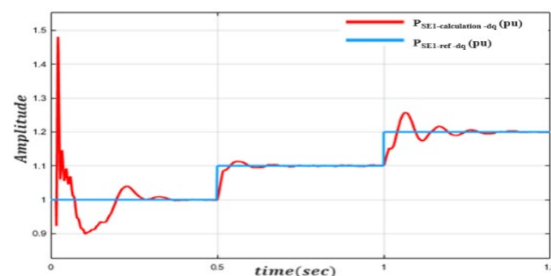


Fig. 13. Active power diagram of series converter 1.

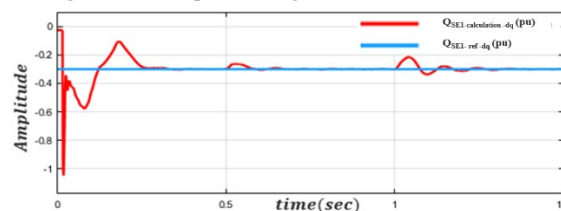


Fig. 14. Reactive power diagram of series converter 1.

C. Simulation results for the output of the GUPFC's series converter 2

Figs. 15 and 16 present the results of active and reactive powers calculated by the control system and the dq reference frame for

series converter 2. In these diagrams, active and reactive powers are calculated using the block diagrams provided in Fig. 5.

It is clearly seen that the values of reference active power for the series converter 2 during the time intervals of 0-0.5 s, 0.5-1 s, and 1-1.5 are 1 p.u., 0.9 p.u., and 1.2 p.u., respectively. Moreover, the reference reactive power for the series converter 2 during the entire period is considered -0.4 p.u. As seen in Figs. 15 and 16, series converter 2 is successful in controlling the active and reactive powers.

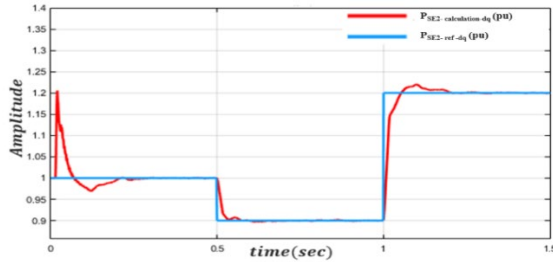


Fig. 15. Active power diagram of series converter 2.

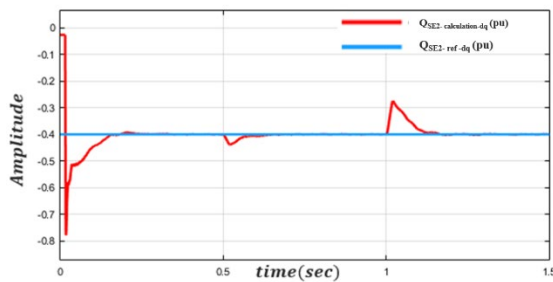


Fig. 16. Reactive power diagram of series converter 2.

D. Simulation results for the active power balance of the GUPFC's three converters

Figs. 17 and 18 present active power diagrams calculated by three-phase voltage and currents measured from buses located at the two ends of series converters 1 and 2. Fig. 19 shows the active power diagram of the shunt converter (Fig. 12) and the sum of active powers of series converters 1 and 2 (Figs. 17 and 18). As is seen from Fig. 19, the active power balance equation for the GUPFC is met.

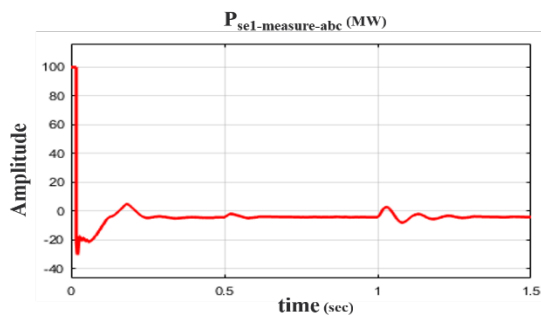


Fig. 17. The measured active power from the transformer of series converter 1.

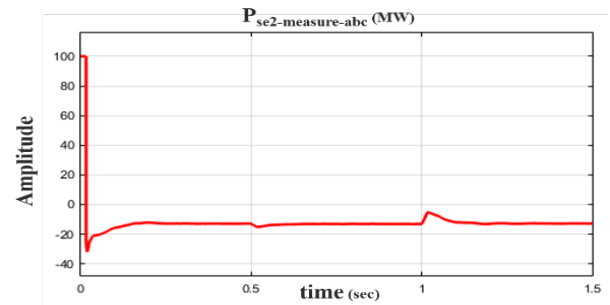


Fig. 18. The measured active power from the transformer of series converter 2.

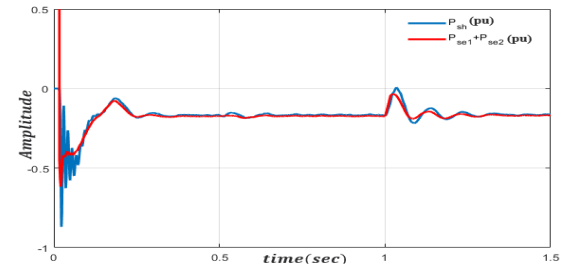


Fig. 19. Active power of the shunt converter along with the sum of active powers of the GUPFC's two series converters.

VI. CONCLUSION

This paper presents the accurate modeling of power injection by a GUPFC placed in the middle of a double-circuit line for the first time. The proposed model is very efficient in static studies such as the power flow. Moreover, accurate modeling of the control system and inverter of the 48-pulse VSC-based GUPFC, specific to dynamic studies, is provided. The control circuit utilized in the current study relies on the dq theory. A new mathematical function that operates based on the PWM theory is presented for the pulse generation system to turn on/off the GTOs of the GUPFC's inverter, where 48 pulses required for turning the GTOs on/off are produced. The suggested technique is robust against noise and can be implemented in various programmable ICs. Furthermore, according to the simulation results, the designed GUPFC can successfully satisfy control constraints and is very effective in terms of improving power quality and reducing harmonic levels.

APPENDIX

The detailed data of the double-circuit transmission line, Thevenin equivalent circuit of both sides of the line, the control system of the GUPFC, power electronic inverter of the GUPFC, and transformers placed between the GUPFC and the transmission line are listed in Table 1.

Table I
Detailed data of the test system.

Line and Source data					
Parameter	Line		Source1		Source 2
V	230 kV		230 ∠ -20.8° kV		230 ∠ 9.2° kV
X/R	-----		10		10
r _l	0.02546	Ohm/km	0.8716	Ohm	1.7431 Ohm
r ₀	0.3864	Ohm/km	1.3074	Ohm	2.6147 Ohm
r _{0m}	0.1732	Ohm/km	0	Ohm	0 Ohm
l _l	0.9337e-3	H/km	0.02576	H	0.05154 H
l ₀	4.1264e-3	H/km	0.00648	H	0.0129 H
l _{0m}	2.01264e-3	H/km	0	H	0 H
c _l	12.74e-9	F/km	info		info
c ₀	7.751e-9	F/km	info		info
c _{0m}	0.575e-9	F/km	info		info
GUPFC data					
Control system					
Shunt Converter			Series Converter		
Nominal power (VA)	200e6		Nominal power (VA)		100e6
Voltage regulator	K _p	12	Current regulator1	K _p	0.5
	K _I	150		K _I	15
Current regulator	K _p	5	Current regulator2	K _p	0.5
	K _I	1		K _I	15
Low pass filter	f _n	100	Mag_Limit	0.25	
	DRZ	0.7			
D_Alpha Blok	K _p	0.001	D_Alpha	0	
	K _I	0.01			
Three level bridge					
Snubber resistance	Rs	(ohm)	1e5		
Snubber capacitance	Cs	(f)	info		
Internal resistance	Ron	(ohm)	1e-4		
Power electronic device	GTO				
Zigzag transformer phase shifting					
Nominal power (VA)			25e6		
Nominal frequency (Hz)			60		
Primary nominal voltage (Volt-rms)			12.5e3		
Secondary nom voltage phase shift (Volt-rms)			12.5e3		
Resistance winding 1 zig-zig (pu)			0.05/30		
Inductance winding 1 zig-zig (pu)			0.05		
Resistance winding 2 zig-zig (pu)			0.05/30		
Inductance winding 2 zig-zig (pu)			0.05		
Resistance winding 3 zig-zig (pu)			0.05/30		
Inductance winding 3 zig-zig (pu)			0.05		

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