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A New Approach to RLC Filter for Harmonic Mitigation Using Genetic Algorithm

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Abstract

A new design method based on the genetic algorithm of phase shift transformers based on passive filters is presented. The method improves the proficiency and precision of the filter. The filter is used in an interface power controller (IPC), an exclusive FACTS device in power transmission. The article spectacles the performance of the projected filter in the IPC structure which expressively diminishes the total harmonic distortion without disturbing the characteristics of the IPC.

Keywords: Genetic Algorithm, Passive Filter, Phase-Shifting Transformer, THD Reduction

1. Introduction

Power electronics applications cover a wide area of electrical drives, uninterruptible power supplies, FACTS, active filters and connection to the grid of renewable sources [1-3]. Hence, Power networks experience high levels of undesirable harmonic distortion which causes more losses, deterioration, and interference in control, communications, and system security, considering that different methods have recently introduced based on communications for control and management of power networks to enhance the energy resiliency [4-5]. Active and passive filters are used to improve power factor and mitigate harmonic currents. Usingactive filters results in highly flexibility while increasing system complexity and costs [6]. Active filters can lead to harmonic elimination in power systems. In [7], a Hilbert Transform based method is used for active power filters to eliminate harmonics in electric railway systems. On the other hand, passive filters are simpler and more economical, offering both power factor correction and high current filtering capability [8]. The harmonic impedances at specific frequencies is designed to be minimized which reduce the overall harmonics of power systems[9-11]. A new method for the design of passive filters with nonlinearities is described in [12-13]. This paper offers a new passive filter model, a combination of the regular RLC circuit with a phase shift transformer (PST). PSTs are vitaldevices to escalate the efficiency and reliability of the system, while dropping operating costs [14-15]. The PST is a cost-effective, and reliable device that ensures efficient power flow control over overloaded transmission lines. The power flow in the transmission network is controlled independently of the generation. The design, construction and operation of PST are exclusive and vary from the standard power transformer [16]. PSTs have been used in overloaded protection, transmission networks and transmission lines. In this work, a PST is used to control the magnitude and phase angle of the equivalent impedance of the filter. It is revealed that the filter preserves all the benefits of regular RLC filters while being more controllable, flexible and precise.This document also presents a new methodology for harmonic mitigation in IPC. The main component of the CPI in each phase is a reactor or a capacitor subjected to voltages supplied by PST. Many types of IPC are possible and each type can have different configurations. This FACTS device guarantees reliable and predictable operation under normal and contingency conditions [17-20]. It has unique advantages, including reduced short circuit, design flexibility, ability to control power transmission in normal mode, and elimination of distortions.However, their performance deteriorates significantly in the presence of harmonic currents [21], and [22]. The importance of harmonic mitigation is accentuated with respect to the use of solar energy [23-24]. It is shown in this document that the application of a passive filter in the IPC significantly improves the performance of that device in the presence of harmonics. The filter is characterized by a simple design, greater reliability and high precision. It is also designed to minimize its impact on the mainstream passing through the IPC while minimizing total harmonic distortion (THD). Harmonicsvary some coming protections in the system. In networks fed by synchronous generators, it is significant to find the appropriate way to establish master or slave generators in island detection [25] and a system of detection of the fast and safe intelligent control mode in the presence of harmonics can be studied further ahead.The document is planned as follows. The characteristics of the IPC and the behavior of the IPC in the presence of harmonics are discussed in Section II. The proposed filter is presented in Section III.The application of the filter in IPC structure is designated in Section IV.A case study to display the performance of the filter in IPC in presence of the harmonic is studied in Section V, and the paper is concluded in Section VI.

2.INTERPHASE POWER CONTROLLER

The IPC involves connection of impedances between different phases of two subnetworks [26].

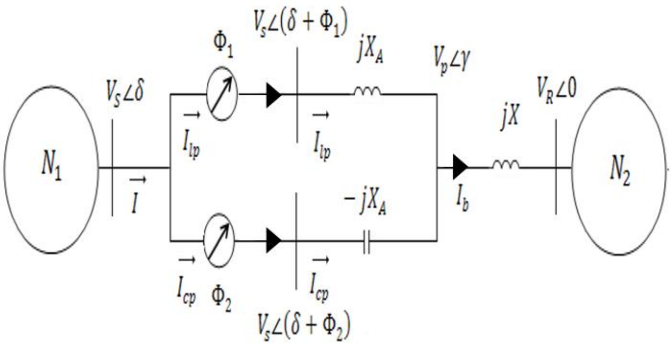

Fig.1.Tuned IPC.

The power flow is nearly constantfor a wide range of the angle between the subnetworks while there is no significant impact on the short circuit vulnerability of the subnetworks. The IPC acts as a current source that generates no harmonics.Any contingencies on one side of the IPC have an insignificant impact on the voltages of the other side. Fig. 1 demonstrates a tuned IPC in series with a transmission line connecting two power systems [27].Expressions for the active and reactive power can be derived from the following equation

$$I_b = \frac{V_S\angle(\delta+\phi_1) - V_p\angle\gamma}{jX_A} + \frac{V_S\angle(\delta+\phi_2) - V_p\angle\gamma}{-jX_A} \qquad (1)$$

where$I_b = I_{cp} + I_{lp}$ is the current of the receiver bus, I_{cp} and I_{lp} are the IPC branch currents, $\delta = \delta_S - \delta_R$ is the phase angle between two busses, V_S is the voltage of the sender bus,Φ_1 and Φ_2 are the phase shifts of the transformers,X_A is the impedance of the capacitor and inductor, and$V_p\angle\gamma$ is the magnitude and phase angle of the voltage right after the IPC. Specifically,

$$(P_S - jQ_S) = V_S\left(I_{lp}^* + I_{cp}^*\right) \qquad (2)$$

$$(P_R + jQ_R) = V_R\left(I_{lp}^* + I_{cp}^*\right) \qquad (3)$$

where P_S and Q_S are the active and reactive power of the sender bus, andP_R and Q_R are the active and reactive power of the receiver bus. The direction of Q_S is opposite to that of P_S, $Q_R$andP_R. Expressions for the active and reactive powers are:

$$P_S = P_R = P_{max}\,.\cos(\delta - \frac{\Phi_1+\Phi_2}{2}).\sin(\frac{\Phi_1+\Phi_2}{2}) \qquad (4)$$

$$-Q_S = Q_R = -P_{max}\,.\sin(\delta - \frac{\Phi_1+\Phi_2}{2}).\sin(\frac{\Phi_1-\Phi_2}{2}) \qquad (5)$$

where $P_{max} = \frac{2V_S V_R}{X_A}$ is the maximum theoretical power flow in the IPC.In practice, the rated power of IPC is limited by the maximum voltages across the inductive and capacitive susceptances.In a special case, if $\Phi_1 = -\Phi_2 = \Phi$,equations (4) and (5) are simplified to

$$P_S = P_R = P_{max}\cos(\delta)\sin(\Phi) \qquad (6)$$

$$-Q_S = Q_R = -P_{max}\sin(\delta)\sin(\Phi) \qquad (7)$$

Under normal operating conditions, the current of the IPC is given by

$$I_b = \frac{V_S\angle(\delta + \Phi_1 - 90) - V_S\angle(\delta + \Phi_2 - 90)}{X_A} \quad (8)$$

$$I_b = -\frac{(V_S\angle\delta)}{X_{IPC}\angle\Phi_{IPC}} \quad (9)$$

Where

$$\Phi_{IPC} = \frac{\Phi_1 + \Phi_2}{2} \text{ and } X_{IPC} = \frac{X_A}{2\sin\left(\frac{\Phi_1 - \Phi_2}{2}\right)} \quad (10)$$

In a special case, if $\Phi_1 = -\Phi_2 = \Phi$,equation (9) can be rewritten to

$$I_b = -\frac{2V_S\sin(\Phi)\angle\delta}{X_A} \quad (11)$$

Equation (11) expressions that the current through the IPC is a gathering of the phase angle (δ), the reactance of the IPC(X_A), the voltage of the sender bus (V_S), and the angle of phase shift (Φ). It should be mentioned that the magnitude of receiver voltage does not affect the current passed through the IPC. The magnitude and the direction of the current are easily controlled by changing the phase shift angle. If the sender bus experiences harmonic voltages, then the bus current is given by

$$I_b = \frac{V_S\angle(\delta + \phi_1) - V_p\angle\gamma}{jhX_A} + \frac{V_S\angle(\delta + \phi_2) - V_p\angle\gamma}{-\frac{jX_A}{h}} \quad (12)$$

Thus, in order to reduce transmission of harmonic currents in the connection between two networks, the equivalent impedance between the networks must increase at harmonic frequencies. Not only does the special structure of IPC preclude it, but it also causes a rapid decrease in the equivalent impedance leading to higher harmonic current transmission in the network.As a consequence, the use of IPC has significantly decreased in practice. Therefore, designing an improved filter for IPC is so important. Designing such a filter is a challenge, as an improper modification can result in a dysfunctional IPC. Thus, the reduction of harmonics must be achieved while the performance and advantages of IPC are retained.

3.PROPOSED FILTER

The projected filter is anarrangement of the RLC circuit and a PST. Themodest and inexpensiveRLC filter is fixed to minimize the main current transientthrough it [26]. The PST makes the filter more controllable and flexible from the design point of view. The main improvement of the filter is that the magnitude and phase of the equivalent impedance of the filter simply can be controlled by regulating the PST. That aids the system to definitely handle the load variations. Altering the phase angle of typical FACTS devices generally does not have emotional impact the magnitude of total harmonic distortion (THD). Nevertheless, in the considered case, the participation of the phase angle helps to regulate the THD. The suggested filter is displayed in Fig. 2.

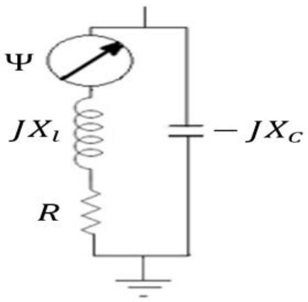

Fig.2.Proposed filter.

As shown, the PST, resistor, and inductor are in the same branch. The equivalent impedance of filter is

$$Z_{eq} = \frac{X_c . X_l - jR . X_c}{R + j(X_l - X_c\angle\Psi)} \qquad (13)$$

and its phase angle is

$$\Theta = -\,\theta - \tan^{-1}\left(\frac{\sin(\theta) - \frac{X_c}{\sqrt{X_l^2 + R^2}}\cos(\Psi)}{\cos(\theta) + \frac{X_c}{\sqrt{X_l^2 + R^2}}\sin(\Psi)}\right) \qquad (14)$$

Thus, the magnitude of the equivalent impedance of the filter is

$$|Z_{eq}| = \frac{X_c}{\sqrt{1 + \frac{X_c^2}{X_l^2 + R^2} - \frac{2X_c . \cos(\theta + \Psi)}{\sqrt{X_l^2 + R^2}}}} \qquad (15)$$

The filter hasan insignificant effect on the fundamental current due to the maximum impedance at the fundamental frequency. The four design parameters used in optimization are determined as follows: X_C and Ψ can be written as

$$X_C = \sqrt{X_l^2 + R^2} \qquad (16)$$

$$\Psi = \tan^{-1}\left(\frac{X_l}{R}\right) - \frac{\pi}{2} \qquad (17)$$

Then, (14) and (15) can be re-written as

$$\Theta = -\theta - \tan^{-1}\left(\frac{\sin(\theta) - \cos(\Psi)}{\cos(\theta) + \sin(\Psi)}\right) \qquad (18)$$

$$|Z_{eq}| = \frac{X_c}{\sqrt{2 - 2\cos(\theta + \Psi)}} \qquad (19)$$

where θ is considered a fixed parameter after the parameter determination. The magnitude and phase of the equivalent impedance of the filter can be significantly changed by adjusting the phase angle of PST.

4.APPLICATION OF THE PROPOSED FILTER IN IPC

The application of the proposed filter in IPC is shown in Fig. 3. A PST alongtworeactances and a resistance are installed as in an IPC employed for power transmission.The proposed filter increases the equivalent impedance of the IPC while preserving the IPC advantages. However, the design of the filter must ensure thatno main-frequency current passes through the filter. There are four design parameters used in optimization, namely reactances X_l and X_c, resistance*R*, and the phase shift Φ_1.According to (16), and (17), two design parameters are dependent on the other two parameters.

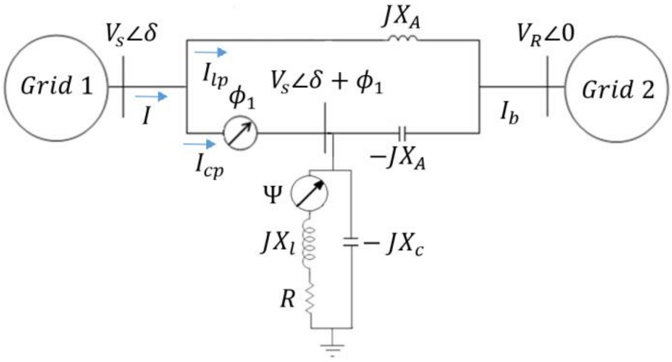

Fig.3. Proposed filter applied to IPC.

Harmonic current passing through the IPC with the filterequals

$$I_h = \frac{V_{Sh}\angle(\delta+\phi_1) - V_R\angle 0}{jhX_A} + \frac{V_{Sh}\angle(\delta) - V_R\angle 0}{-\frac{jX_A}{h}} - \frac{V_{Sh}\angle(\delta+\phi_1+\Psi)}{-\frac{jX_C}{h}} - \frac{V_{Sh}\angle(\delta+\phi_1)}{jhX_l + R} \quad (20)$$

where*h* symbolizes the harmonic number. The fundamental current and THD are given by

$$I_1 = \frac{V_S\angle(\delta+\phi_1) - V_R\angle 0}{JX_A} + \frac{V_S\angle(\delta) - V_R\angle 0}{-JX_A} \quad (21)$$

and

$$THD=\sqrt{\sum_{h=2}^{n}\left(\frac{I_h}{I_1}\right)^2} \quad (22)$$

In view of reduction of the THD, Equation(20)indicates the harmonic currents at the receiver bus be subject tonine circuit parameters[28, 29]. Five known, including the voltages at the busesV_S and V_R, the phase angle δ, the phase-shift angle Φ_1, and the reactance of the IPC,X_A. Four parameters,containing the impedances of the filter, X_C, X_L, and R, and the angle of phase shift Ψ, are unknown and need to be adjusted. Hence, the objective function in (22) is nonlinear. The THD can bediminishedusing a genetic algorithm (GA) constructed on the IPC conditions and limitations. As point outbefore, only the X_l and R parameters in (22) must beadjusted by the GA as the other two parameters, X_C and Φ_2, are functions of them.

5.CASE STUDY

The Vattenfall'sOrmonde Offshore Wind Farm (OOWF) from [23] was employed as the sender bus. The first seven harmonic voltages were used in this case study. Total harmonic voltage distortion was calculated. Table Iexpresses the equivalentvoltages and equivalent impedances of OOWF.

TABLE I HARMONIC VOLTAGES AND EQUIVALENT IMPEDANCES OF OOWF

V_2	V_3	V_4	V_5	V_6	V_7	R_{th}	X_{th}
0.055	0.159	0.056	0.408	0.064	0.326	0.147	0.32

The receiver bus is a photovoltaic (PV) system, which involves of a PV array, a diode, an inverter, and a power grid interface [30]. The PV array is estimated by the one-diode model. The inverter takes out the maximum power from the array via the incremental conductance method and delivers the extracted power at a unity power factor. The expected grid impedance,Z_{th}, is 0.095+j0.012 Ω, and the IPC runs under normal conditions. To avoid series resonance, the slightest value of IPC reactance, X_A,was set to 0.2 Ω, which is largerthan $10 \times Z_{th}$. The phase shift was set to 17.5^o.The IPC failed to mitigate the harmonic distortion while intensifying the harmonic currents. The THD was found to be 1.33.

TABLE II SIMULATION RESULTS

THD	$X_C(\Omega)$	$R(\Omega)$	$\Psi(deg)$	$X_L(\Omega)$
0.045	5.2	5	77	1.3

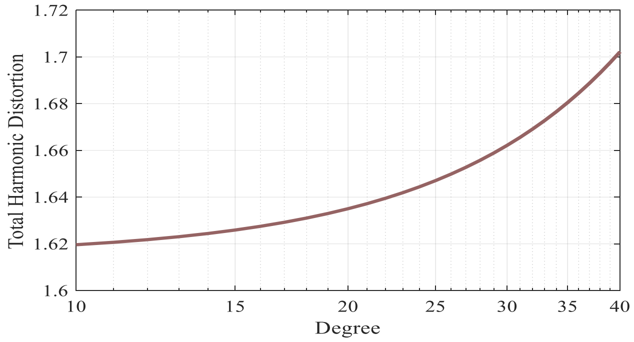

Fig.5. THD versus the main phase shift with no filter.

The probable improvement of the THD may come from the main PST. Nevertheless, as seen in Fig. 5, phase variations by the PST do not have a significant influence on the THD.In the following, the performance of IPC in presence of the proposed filter will be discussed.In this case, according to (16) and (17), the reactance $X_C$of the capacitor and the filter PST's angle Ψ depend on the reactance X_L of the inductor and the resistance *R*of the filter. The GA was employed to determine the minimum THD, and Table II shows the results. The minimum THD of 0.045corresponds to $\Psi \approx 77^o$.Table III shows the sensitivity of THD to parameters of the IPC and filter.The sensitivity of THD to the parameters was measured when the parameters changed by $\pm$10%, $\pm$5%, $\pm$2.5%, and $\pm$1%. It can be seen thatthe reactance of the line, X_A, the capacitor reactance of the filter, X_C, and the phase shift $\Psi$of the filter strongly affect the THD, while the impact of *R* and X_l is not significant.

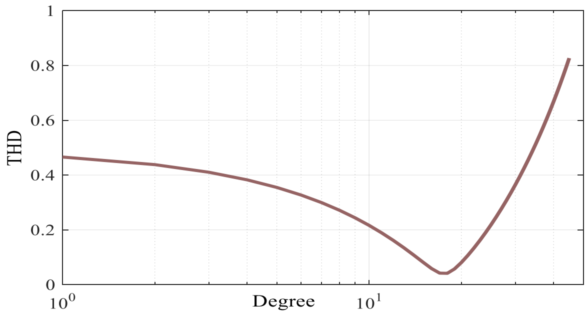

Fig.6. THD versus Φ_1 with the filter.

TABLE III SENSITIVITY OF THE THD TO PARAMETERS OF THE IPC AND FILTER

%	X_A	Φ_1	Ψ	X_C	X_L	R
-10	3.2	0.74	4.5	3.78	0.067	0.2
-5	1.65	0.32	1.89	1.45	0.032	0.08
-2.5	0.57	0.07	0.8	0.46	0.022	0.04
-1	0.09	0.02	0.2	0.067	0.007	0.02
1	0.09	0.002	0.24	0.098	-0.002	-0.02
2.5	0.37	0.024	0.77	0.5	-0.005	-0.03
5	1.36	0.24	1.87	1.26	-0.0004	-0.05
10	2.4	0.8	4.9	2.8	0.023	-0.1

The impact of the IPC PST's angle(Φ_1)on the THD is illustrated in Fig. 6.

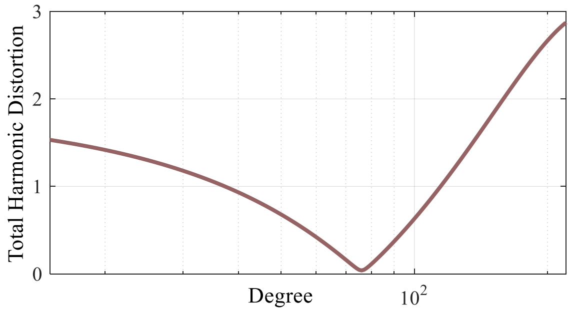

Fig.7.THD versus Ψ and $\Phi_1$with the filter.

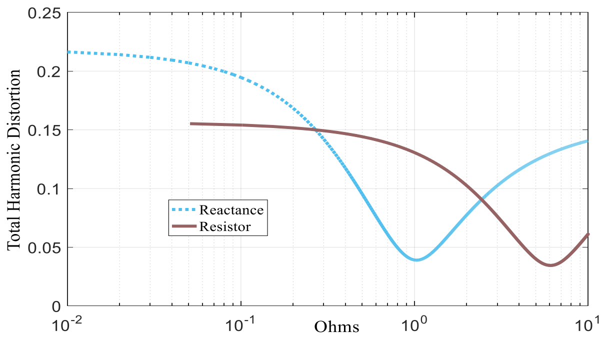

Fig 8.THD versus reactance and resistance of the filter.

Fig. 7 spectacles the changes in the THD when angles$\Phi_1$and Ψvary between 0^o and 360^o, and the weak dependence of THD onthe reactance and resistance of the filter is illustrated by Fig. 8. Fig. 9 explains the magnitude and phase of the equivalent impedance of the filter for diverse harmonics. The impedance declines rapidly in the low harmonic range.The magnitude of the impedance is 4.7Ω, while for the 9th and 21stharmonics the impedances are, correspondingly, 0.8Ω and 0.28 Ω.

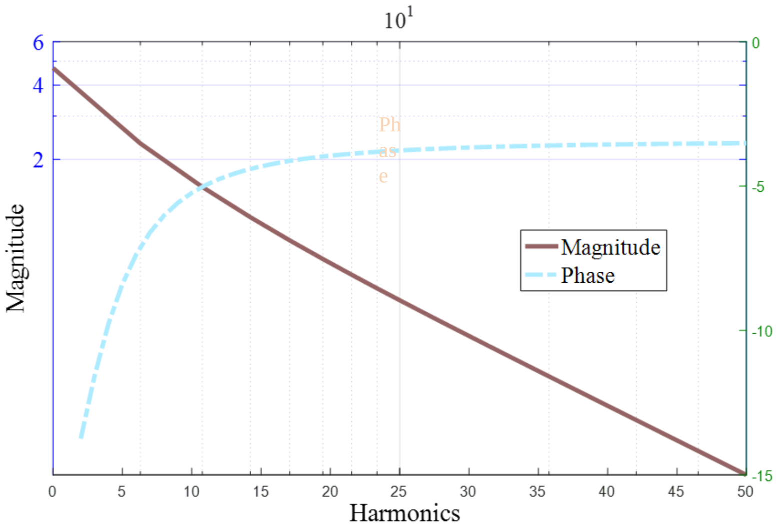

Fig.9. Magnitude and phase of the equivalent resistance of the filter.

Therefore, for high harmonics the filter deliversan increasingly low impedance, absorbing harmonics currents and mitigating the THD.

6.CONCLUSION

A new design of IPC with a passive filter and PSTs has been proposed. Compared with the traditional RLC passive filter, it expressivelydiminishes the voltage THD without any performance worsening.Easiness and low maintenance requirements are additional compensations of this IPC. The novel IPC desensitizes harmonic mitigation from changing load condition and the phase angle of PST.

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