Assessment of active filter on transformers connected three phase bridge converters

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Abstract. This paper starts with the benchmark analysis of shunt active power filter (SAPF) for adjusting either compensations of harmonic current or compensating reactive power. Such equipment can capable of minimizing the content of harmonics present in the grid side generated by the non-linear loads. The proposed work represents the proficient response of shunt active power filter for annihilates the contents of harmonics to keep the better quality of power supply. The implementation of SAPF on three-phase bridge (TPB) converters associated with cascaded single-stage transformers has been introduced. The transformers arrangements allow the compensator to utilize one dc-link unit that simplifies the management strategy and the mode of operation. The system waveforms are provided by employing an appropriate pulse width modulation (PWM) technique having good correlation with transformer turn ratio. System overview and easy maintenance create the projected SAPF has an efficient solution related with some standard previous configured model. The proposed model, PWM method and the control managements are given also as studies considering non-linear distortion and switching losses estimation. A MATLAB Simulink has been used to validate the implementation of SAPF based on Cascaded Transformers Coupled with Three-Phase Bridge Converters.

Keywords. Shunt Active Power Filter (SAPF), three-phase bridge (TPB), Phase shifting Pulse width modulation (PWM)

1. Introduction
Use of non-linear loads leads to generates harmonic content which may create power quality problem in entire power system. The common disturbances present in power systems because of:

- Under voltage
- Harmonics present in voltage and current.
• Voltage surge phenomenon.
• Transient and interruptions.
• Flickers
• Symmetrical and Unsymmetrical Faults

Usually, an unlike inductive load and the non-linear loads are mostly responsible for current harmonics injection and reactive power present to the grid, which leads to adverse effect on system stability and poor power quality. In the early stage, LC filter has been taken into consideration to remove harmonic content; however the solutions are inefficient because of limited reactive power compensation and resonance effect on entire power system. To mitigate this active power filters (APFs) design has been introduced [1, 2]. The APFs has classified into three types.

• Series APF [3]
• Shunt APF [4-6]
• Unified power quality conditioner (UPQC) [7-8]

In this paper shunt active power filters (SPAF) has considered because of following advantages:

• Effective compensation of current harmonics for non-linear loads,
• Making current balance from imbalance condition,
• Providing better power quality

Shunt Active power filters consist of Converters, DC-link capacitors, chocked inductors, and isolation transformers [2-10], in this paper, the SAPF has the combination of voltage source converter and isolation transformer. There are various group of topologies has been used to design converters (voltage source/current sources converters), the combination of voltage sources converter (VCs) and isolation transformer has been used to design SAPF. There are various type of configuration has been used to design VCs. The most common type of configuration is 2-lavel used for low power application. However for high power application, multilevel VCs are commonly used, the complexity problem may arises with the use multilevel inverter because of DC-link capacitors. Since the high number of capacitors may leads to increase the possibility of failure in SAPF henceforth, the cascaded transformers may be the options to deals with these issues.

An ordinary SAPF with series transformer combined with H-connect (HB) converters was introduced and noted that, cascaded transformers are capable of providing isolation in between power supply and SAPF and great reliable concerning to dc-link capacitors as well. The present research work includes an arrangement of SAPF, cascaded transformer incorporated with three phase bridge converter (TPBC) can see in fig 1. Such arrangement may capable of achieving multilevel operation with less number of switching devices for K-stage with k-number of three phase transformer incorporated with TPBC. The generated waveform from multilevel operation of converter using pulse width modulation (PWM) control strategy is quite comparative then conventional converters. To validate this MATLAB [11-14] simulation has been performed.

2. System configuration
The arrangement in Fig. 1 is showing for K-stage arrangement in between k-stage of three phase transformers and converters [1]. Since the converters are three phase, legs of the converters are represented 2K phase and 6K for each stage of converter.

The converter shaft voltages \( v_{kj0}, v_{kj0}, \ldots v_{kj0} \), represented as

\[
v_{kj0} = (2qkj - 1) \frac{v_C}{2}(1)
\]
Where \( k \) represents number of stage \((i.e., k = 1, 2, 3, ... K)\) \( j \) associated for each stage \((i.e., j = a, b, c, ... )\) and \( v_c \) represents DC-voltage.

Keeping leakage reactance of transformers, shunt reactance \((l_{sh})\) and losses because of shunt resistor \((r_{sh})\) into an account, the entire voltage equation of SAPF has expressed as

\[
v_{rj} - v_{gs} = l_{sh} \frac{di_{sj}}{dt} + r_{sh}i_{sj} - l_g \frac{di_{gj}}{dt} - r_g i_{gj} + e_{gj} \tag{2}
\]

Where \( v_{rj} \) is the resultant voltage of the converters identified with the optional voltages of the scaled transformers and \( v_{gs} \) is the potential difference in between two points \( g \) and \( s \). applied nodal technique to express the current equations as

\[
i_{sj} = i_{ij} - i_{gj} \tag{3}
\]

Where the load currents \( i_{ij} \) are given by the load model.

Substituting equation (3) in (2)

\[
v_{rj} - v_{gs} = -(l_g + l_{sh}) \frac{di_{gj}}{dt} - (r_g + r_{sh})i_{gj} + l_{sh} \frac{di_{ij}}{dt} + r_{sh}i_{ij} + e_{gj} \tag{4}
\]

The last two terms present in right hand side of equation 4 is representation the disturbances which can be recompense by the controllers. The transformer voltages at the optional side of every transformer \((v_{1j}, v_{2j}, ..., v_{Kj})\) are related with \( v_{rj} \) such that

\[
v_{rj} = v_{1j} + v_{2j} + v_{3j} + \cdots + v_{Kj} \tag{5}
\]

where \( v_{1j}^1 = N_1(v_{1j0} - v_{10}), v_{2j}^1 = N_2(v_{2j0} - v_{20}),..., v_{Kj}^1 = N_k(v_{kj0} - v_{k0})\), in which \( N_1, N_2, ..., N_k \) are the transformer turns proportions related with converters \( I, 2, ..., K \), respectively.

Considering and ideal isolation transformer the yield voltages \( v_{rj} \) of the resultant converter can be written as

\[
v_{rj} = v_{rjo} - v_{ro} \tag{6}
\]

\[
v_{rjo} = N_1v_{1j0} + N_2v_{2j0} + \cdots + N_kv_{kj0} \tag{7}
\]

\[
v_{ro} = N_1v_{10} + N_2v_{20} + \cdots + N_kv_{k0} \tag{8}
\]

The presumed system having balanced three phase three wire system \((i.e., v_{ka} + v_{kb} + v_{kc} = 0)\) and \( i_{ka} + i_{kb} + i_{kc} = 0 \) the voltage \( v_{ro} \) can be expressed by

\[
v_{ro} = \frac{N_1}{3} \sum_{j=a} v_{1j0} + \frac{N_2}{3} \sum_{j=a} v_{2j0} + \cdots + \frac{N_k}{3} \sum_{j=a} v_{kj0} \tag{9}
\]

Substituting (9) in (6) will give

\[
v_{rj} = v_{rjo} - \frac{N_1}{3} \sum_{j=a} v_{1j0} + \frac{N_2}{3} \sum_{j=a} v_{2j0} + \cdots + \frac{N_k}{3} \sum_{j=a} v_{kj0} \tag{10}
\]

It has been seen that the voltage \( v_{rj} \) need to be keep on maximum levels of voltage \( (v_{rjo}) \) presuming appropriate state of switching sequences, can accomplish by varying the turns ratio of the transformers. A specific case of 3-phase transformers with 3 three phase bridge converter (TPB) converters for the series compensation has been studied and found that voltages \( v_{rj} \) may get up to 8.
unique levels depending on their switching level, which can done only when transformers operate with different turns ratio \((i.e., N_k = 2(k - 1))\).

\[ N_k = 2^{(k-1)} \]

**Figure 1.** Studied test model [1].

Such arrangement may help to mitigate harmonics distortion present in the power converters. It has been observed that, if transformers turn ratio considered as \(N_k = 2^k\) then there is no redundant levels found. The redundant level only can found if two or more transformers are having same turn’s ratio \((i.e., N_1 = N_2 = 1)\). Using redundant property, improving other features accomplishing with power converters.

3. **PWM Technique**

The proposed work used pulse width modulation (PWM) technique based on level shift carrier based in which takes references to get an output voltage \(v_{rj0}\), the references for the PWM technique are given by
\[ * v_{rj0} = v_{rj}^{**} + * v_{rots} \] (11)

Where \( v_{rj}^{**} \) representing references provided by current controllers, and \( * v_{rots} \) has defined in eq (7). \( * v_{rots} \) represents as a variable quantity which control degree of freedom. The reference voltage for \( * v_{rots} \) can expressed as

\[ * v_{rots} = * \mu_{rots} \cdot * v_{rots\ max} + (1 - * \mu_{rots}) \cdot * v_{rots\ min} \] (12)

Where \( 0 \leq * \mu_{rots} \leq 1 \)

\[ * v_{rots\ min} = -0.5 \cdot v_c (N1 + \ldots + NK) - \min \{v_{rj}^{**}\} \] (13)

\[ * v_{rots\ max} = 0.5 \cdot v_c (N1 + \ldots + NK) - \max \{v_{rj}^{**}\} \] (14)

Where \(( * v_c \) represents reference voltage of DC-link.

The comparison in between reference voltages \( * v_{rj0} \) and \( 2^n - 1 \) triangular waveforms has been placed according to levels and observed that it is providing a comparison of switching states which has been applied for each converter.

4. Control strategy

The layout of control strategy has been shown in Fig. 2, where \( v_c \) representation Dc-link capacitor voltage which has been supervised by the controller blocks RC [1]. The output of Controller RC is the reference current of three phase system, the references current \( i_{gb}^* \) and \( i_{ga}^* \) may get by synchronizing their respective phase \((i.e., e_{gb}, e_{ga})\) supplied by Block \( S_{in} \) whose input has been provided by phase locked loop (PLL) block. The references voltage \( v_{rj}^{**} \) and \( v_{ra}^{**} \) has been defined by the controller block \( Ri_{ab} \) which has used as reference signal in PWM. The function of controller’s block RC and \( Ri_{ab} \) are used as ordinary Proportional controller (PI-Controller) and Resonant PI-controller respectively. The more details of PWM may be found in [15].

![Figure 2. Studied control method [1].](image-url)
5. Simulation results
Simulation results through MATLAB version 2016 has been used to validate results. In Fig.3 and 13 shown, simulation block diagrams of cascaded transformer for 2-turn and 3-turn respectively and the simulation results of cascaded transformer terminal voltage has shown in Fig 8 and 14. To drive SAPF, a level shifted pulse width modulation technique for 2-turn and 3-turn has shown in Fig 4 and 9 respectively, used to maintain the active filter currents in phase with the grid currents by using phase locked loop. Fig.5 shows the voltage sag condition at the time of 0.15s to 0.35s, this sag is created in the source side of the power system; the shunt active power filter operates to inject complementary voltage in terms of power shown in Fig.6. The linear transformers are used to inject complement voltage, then the sinusoidal voltage is achieved Fig.7 at the output side of power system i.e. (load side), which is in phase with the grid currents. It has been seen in Fig. 10-12, width of the pulse decreasing with increasing turn of transformer windings which shows there is an inverse relation in between turns of transformer windings and the width of the pulse.

![Figure 3. Simulation diagram of cascaded 2 turn transformer.](image)

![Figure 4. Level shifting pulse width modulation (LSPWM) for 2 turns winding.](image)
Figure 5. Source voltage per phase A ($V_{Sa}$).

Figure 6. Compensating voltage per phase A ($V_{Ca}$).

Figure 7. Load voltage per phase A ($V_{La}$).
Figure 8. Cascaded transformer terminal voltage ($V_{ra}$).

Figure 9. Level shifting pulse width modulation (LSPWM) for 3 turns winding.
Figure 10. Cascaded turn 1 winding transformer ($V_{1a}$).

Figure 11. Cascaded turn 2 winding transformer ($V_{2a}$).

Figure 12. Cascaded turn 3 winding transformer ($V_{3a}$).
6. Conclusion
Design of shunt active power filter has been discussed in this paper. Designing of SAPF has an arrangement of cascaded transformer with three phase bridge converter, leads to reduce harmonic content by reducing WTHD estimation. The estimated harmonic content has improved which also leads fixation of switching losses. In short, the following conclusions can be found in the study.

Figure 13. Simulation diagram of cascaded 3 turn transformer.

Figure 14. Cascaded transformer terminal voltage ($V_{ra}$).
- The proposed method explained practically in different stages and seen that SAPF has an advantages and improvement of the power quality at the signs produced by the PWM converter.
- The quantity of levels created at the voltage $V_{rj}$ for the introduced design is more efficient when compared with the previous configurations based on the same number of switches.
- To balance the switching losses, the proposed system is operated with various number of stages.

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