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Improved Instantaneous PQ Theory based Reference Current Generation Algorithm for Shunt Active Power Filters

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Abstract;- **Performance of an active power filter mainly depends on accurate generation of reference current. The most commonly used method is the instantaneous PQ theory based reference current generation scheme. Although it is advantageous in many aspects, but it fails to achieve desirable compensation results under unbalanced supply voltage condition in three phase electrical power systems. Therefore this issue is addressed in this work and a suitable improved version of Instantaneous PQ theory is presented. The proposed theory is validated by the results obtained through simulation based studies.**

Index Terms: **Power Quality, Harmonics, Shunt Active Power Filter, Reference Current Generation Algorithm.**

I. INTRODUCTION

In recent times increasing applications of power electronic devices have brought up challenges for maintaining good quality of power. Over the years, passive filters are being used for this purpose. In spite of being simple and economical, it however fails to satisfy modern age challenges, such as variation in source and load condition, suppressing resonance, compact in size, light weight etc. Therefore, to achieve these requirements active power filters (APF) are now being used in the field of industrial electrical systems. The basic principle of APF is to utilize power electronics devices to produce harmonic current components drawn by the nonlinear load. When such APF is connected to the system it relieves the supply source from producing the harmonic component demanded by the non linear load and hence maintains clean A.C. supply voltage and current. Many review reports[1]-[2] on the working of active filters are given in the literature. Out of the two configurations available, namely shunt and series type, the shunt active power filter is mostly used since it does not carry the load current and can be easily maintained without interrupting the main power circuitry thereby being more reliable [3].
Proper functioning of these shunt active power filters (SAPF), require accurate generation of reference current from the measured load current signal [2]. This process of reference current generation is considered very important as it involves estimation of magnitude, phase, frequency etc. accurately and instantaneously, so that the controller can respond promptly to the everlasting load changes. Other issues like computational and data storage overhead, sensitivity to change of working conditions, implementation complexity, etc., also needs to be taken into account in the formulation of reference current generation algorithm. Therefore various algorithms such as instantaneous PQ theory (IPQT)[4], synchronous reference frame method or DQ theory [5], Artificial Neural Network (ANN) [3], adaptive learning[6], nonlinear least square based method [7], Wiener filters [8], Gauss –Newton based recursive algorithm [9], empirical mode decomposition based algorithm [10], recursive least square method [11], etc. has been proposed from time to time.

However instantaneous PQ theory and synchronous reference frame method (DQ theory) of reference current generation are found to be most commonly used in real time shunt active power filters (SAPF) [8] due to their better response ability under different kinds of practical fault situation like variation on load side parameters, supply frequency variation etc. Under conditions of frequency variation, the results of DQ theory are observed to deteriorate as it involves the use of phase locked loop (PLL) whose speed is found to be quite slow in frequency estimation process [12]. As for instantaneous PQ theory, it does not involve any complex calculation such as PLL, adaptive or neural network based parameter estimation process etc. and simultaneously also provide satisfactory result in most of the fault conditions. But its ability to compensate supply side harmonics degrades only in unbalanced three phase system [13]. Therefore the objective of this study was to add necessary improvement to the original IPQT algorithm of reference current generation such that it performs equally well even under conditions of unbalance in three phase electrical system. Comparative analysis between this improved PQ theory and original PQ theory and DQ theory method is also performed to validate the proposed theory. The proposed method and its subsequent results along with necessary explanations are presented in section II, III and IV respectively. Finally conclusion of the current research work is thereby presented in section V.

II. METHODOLOGY

A. Design of SAPF

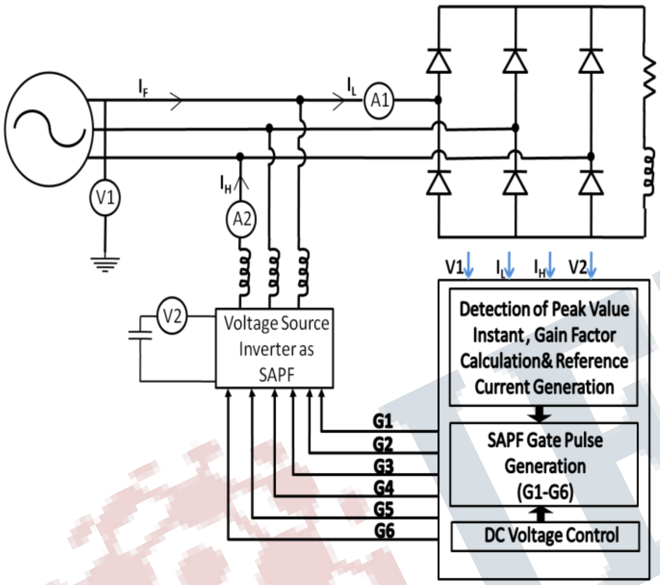


Fig. 1 Block Diagram Representation of SAPF modeled in SIMULINK environment

To perform this study a SIMULINK model of shunt active power filter with system parameters presented in Table 1, is developed. The block diagram representation of the model as shown in Fig. 1, comprises of a three phase diode bridge rectifier with R load on the rectified side, as the non linear load. Supply voltage , load current and direct voltage across the SAPF voltage source inverter are measured and given as inputs for reference current generation by both the original and improved PQ algorithms. This generated reference current when compared with actual SAPF current output, provides the gate pulses required by SAPF to supply the harmonic components of the nonlinear load current hence compensate the supply current. PWM control method is used for gate pulse generation in this work [14].The performance measure of these algorithms are based on the percentage total harmonic distortion (THD) value of compensated supply current which should be within 5% as per IEEE 519 standards [15].

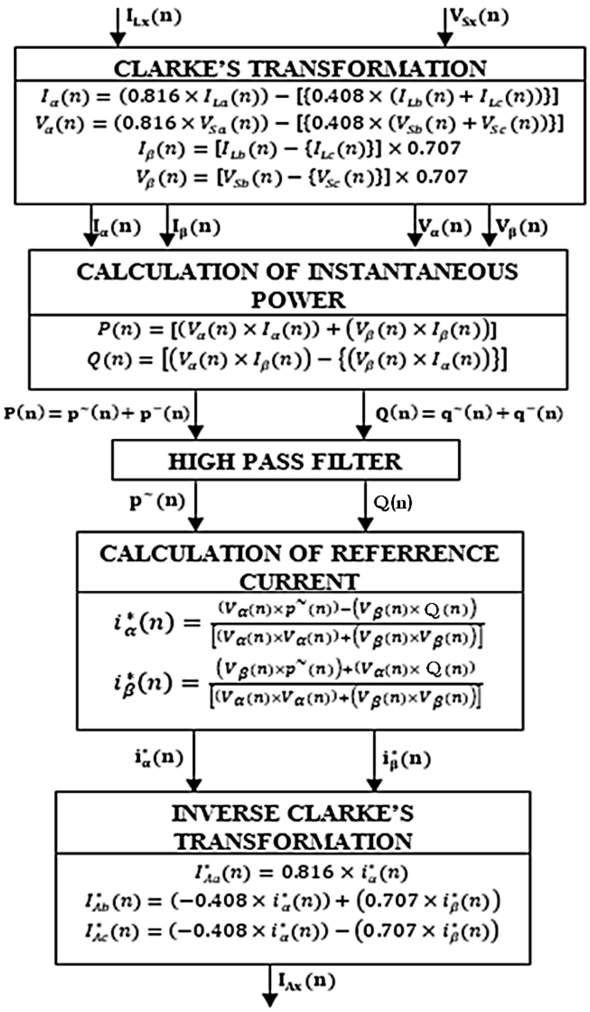
Table 1: SAPF system parameters as used for simulation

Parameter	Value
Line-Line Voltage, Frequency	100V, 50Hz
Source Inductance	0.1mH
DC Link Capacitor	2200uF
DC Link Voltage	300V
Filter Inductor	5mH
Non Linear Load	3-phase diode bridge rectifier.

B. Proposed Improvement of IPQT algorithm

The basic PQ theory method of reference current generation involves conversion of three phase measured voltage and current data acquired into two phase data in the first step. Next total active power and reactive power that can be generated from this measured current and voltage amount, is extracted. This total active and reactive power includes power generated from fundamental component of load current and supply voltage, as well as that generated from the harmonic components also. After that the active power drawn by harmonic components and total reactive power is extracted with the help of a high pass filter. This power values are used to generate the required reference current for the shunt active power filter. In this way the reference current that is generated comprises of all the harmonic components of the load current and is also able to achieve unity power factor condition between the line current and voltages. The mathematical representation of this method including the various equations used for calculation of the reference current is presented in the form of a block diagram in Fig. 2, wherein ILx represents load current for all the three phases(x), Vsx represents supply voltage measured for all three phases, IAx represents the three phase generated reference current and n symbolizes each time instant .

Fig. 2 Mathematical representation of original IPQT based reference current generation algorithm



However it is observed that in case of unbalanced supply voltage condition, if no modification is applied on the measured voltage data, then it results into poor compensation of the supply current. The percentage THD value of the compensated supply current is found to be much higher than 5% limit as prescribed by IEEE 519 standards. This additional modification required is not included in the original PQ theory method. Therefore this work presents the improved PQ theory method which includes the required modification to be added in the original method. The block diagram representation of the improved method is as shown in Fig. 3.

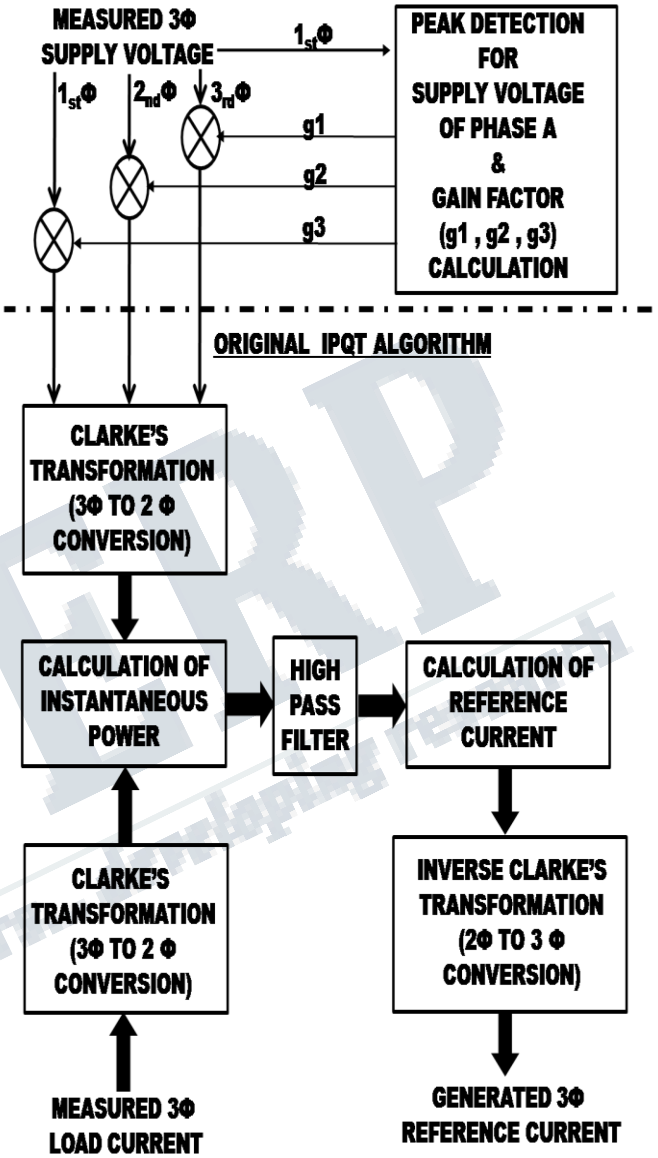


Fig.3 Block Diagram representation of improved IPQT based reference current generation algorithm

This particular improvement included in the original PQ theory method as presented in the above figure aims to determine the percentage unbalance in the system. Now, for balanced three phase sinusoidal waveform, peak value of any one waveform corresponds to 50 % of the peak value for other two waveforms. This is illustrated in Fig. 4.

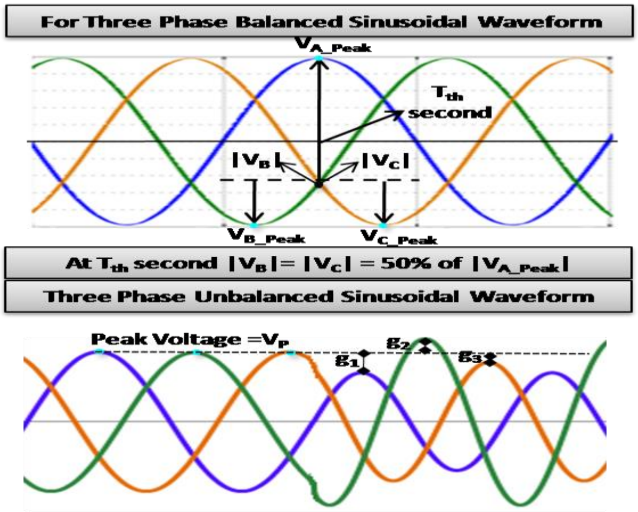


Fig. 4 Unique feature of three phase balanced sinusoid (top) and necessary gain factors g1,g2,g3 for eliminating the unbalance (below).

When an unbalance occurs in this three phase system gain factors g1, g2, g3 has to be calculated to restore the system into balance condition. The procedure to find out these gain factors is discussed as follows:

Let Vp be the peak to peak supply voltage value under balanced condition. At first, peak value VA_Peak¬ for phase A of supply voltage is determined by applying a peak detection algorithm. Therefore at the peak point P the factor g1 by which phase A is unbalanced can be obtained by

g1=|Vp|/VA_Peak|...(1)

Next the unbalance factor (g2) in phase B is determined. The magnitude of phase B supply voltage obtained at peak value of phase A, named as |VB|, should be 50 % of Vp under balanced condition. Therefore,

g2=(0.5*|Vp| / |VB|……………………………………(2)

Finally the unbalance factor in phase C of supply voltage is similarly obtained from

g3=(0.5*|Vp|)/ |VC|……………………………………(3)

In this way once the three gain factors are obtained they are multiplied with the measured supply voltage data and then sent into the Clarke transformation block for three phase to two phase conversion. The measured load current data is sent unmodified into the Clarke transformation block for further calculations. Rest of the algorithm applied is same as the original PQ theory method as shown in Fig.3.

So it is observed that peak detection algorithm plays an important role in this entire process, Thus a detailed explanation of the proposed peak detection algorithm is presented in the next sub section..

C. Implementation of Proposed Peak Detection Algorithm in Digital System

First of all the algorithm takes three consecutive samples of the measured supply voltage namely Vs(n), Vs(n-1) and Vs(n-2) as input, at time instant n. Next the variables X,Y and Z are obtained using equations 4, 5 and 6.

X=|0– Vs(n)|……………………………………………(4)
Y=|0–Vs(n-1)|…………………………………………(5)
Z=|0– Vs(n-2)|…………………………………………(6)

Finally it is checked if numeric value Y is greater than X as well as Z, because this condition occurs if and only if the current time instant corresponds to the data value just after the required peak value. If this condition is met then the voltage signal value Vs(n-1) is obtained as peak value of measured supply voltage. Block diagram representation of the algorithm is presented in Fig. 5.

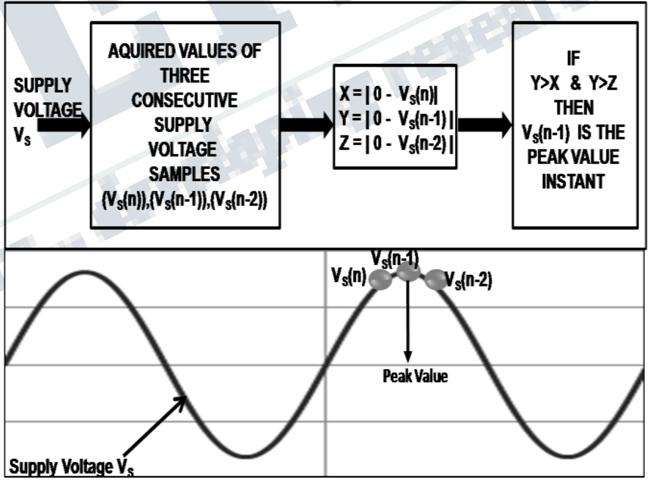


Fig. 5 Block Diagram Representation of proposed peak detection algorithm.

III. RESULTS

This section presents the comparative analysis between results obtained from original PQ method and proposed improved PQ method of reference current generation for SAPF when applied on balanced as well as unbalanced supply voltage condition.

Case 1 : Under Balanced condition of three phase supply voltage.

This study was particularly performed to verify whether the improved PQ method was able to perform as robustly as the original PQ method under conditions of balanced three phase system.

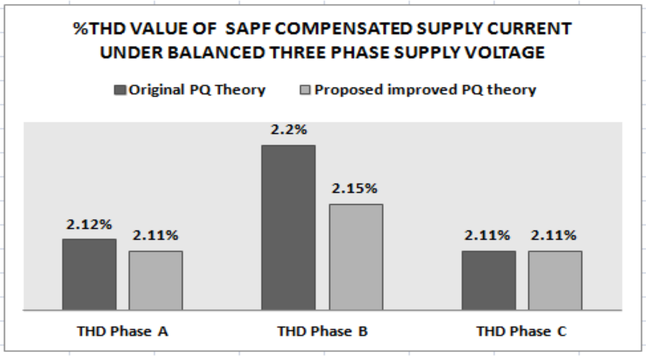
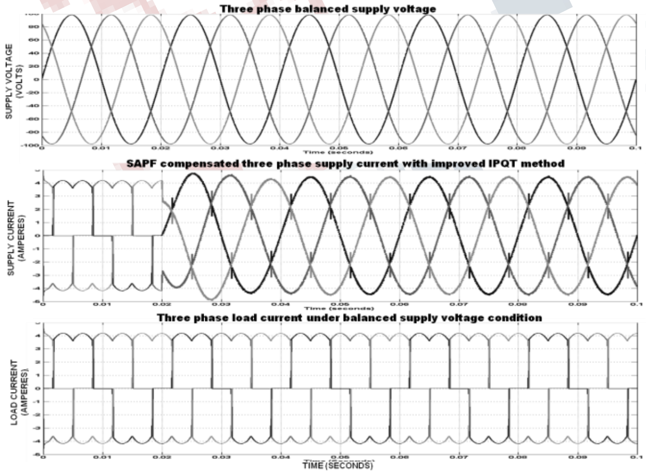


Fig. 6 Comparative study based on percentage THD of compensated supply current obtained with SAPF under balanced three phase supply voltage condition, using original and improved IPQT.

Desirable results was observed in this case as shown in Fig. 6 and Fig. 7, presenting the applied supply voltage and compensated supply current waveform along with three phase load current as obtained from simulation experiments.

Fig. 7Improved IPQT performance for balanced three phase supply voltage



The supply current %THD value obtained after SAPF compensation using the proposed reference current generation algorithm, was found to be 2.11% for phase A, 2.15% for phase B and 2.11% for phase C. Also since the improvements were applied only on the measured supply voltage leaving the rest of the original PQ algorithm undisturbed, the results obtained for load variation and supply frequency variation was equally good as the original algorithm.

Case 2 : Under unbalanced condition of three phase supply voltage

In these set of experiments , magnitude of voltage in phase A of the three phase system is reduced by 30 % to create an unbalance in the system at time instant t = 0.06 sec. As observed from the results obtained, shown in Fig. 8 and Fig. 9 respectively, the %THD value of compensated supply current for all the three phases came down to values like 1.77% for phase A, 1.72% for phase B and 1.67% for phase C, only after applying the proposed improvement in the original PQ method.

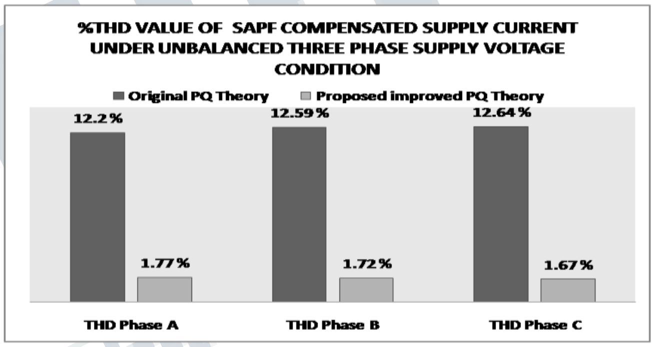


Fig. 8 Comparative study based on percentage THD of compensated supply current obtained with SAPF under unbalanced three phase supply voltage condition, using original and improved IPQT.

A comparative analysis is also performed between four types of reference current generation algorithm in terms of percentage THD compensation capacity of SAPF. Apart from the proposed method, data of four other methods are taken from [16] as shown in Table 2 for the comparative study under balanced and unbalanced condition of supply voltage.

The percentage THD compensation capacity is calculated as follows:-

$$\%THD\ compensation\ capacity = \left(\frac{\%THD\ before\ SAPF\ compensation - \%THD\ after\ SAPF\ compensation}{\%THD\ before\ SAPF\ compensation}\right) \times 100$$

The results obtained for this comparison is presented in Table 2 which reveals better performance of the proposed improved PQ method over all the other commonly used methods of reference current generation for SAPF.

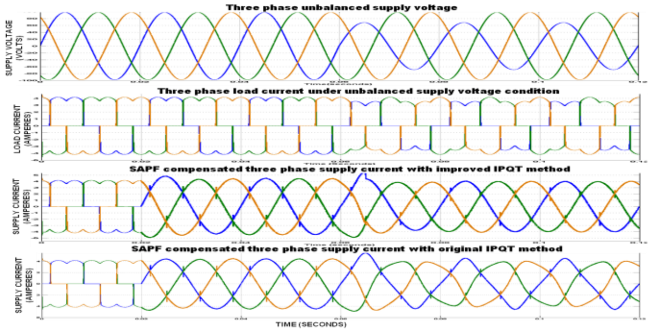


Fig.9 Comparative analysis between original and improved IPQT based SAPF performance with respect to compensated three phase supply current.

Table 2: Percentage THD compensation capacity of SAPF as obtained with different algorithms under various supply voltage condition

Supply Voltage Condition	Supply Current Phase	Percentage THD compensation capacity of SAPF				
		PQ Theory [16]	Modified PQ Theory[16]	SRF-PLL Method [16]	Modified DQ Theory[16]	Proposed Improved PQ Theory
Balanced	A	83.8	85.1	84.2	84.3	**92.9**
	B	84.3	87.3	85.1	85.5	**92.8**
	C	86.0	87.7	85.5	85.7	**92.9**
Unbalanced	A	67.3	76.7	84.7	85.8	**94**
	B	85.1	89.6	93.1	93.3	**94.2**
	C	64.6	74.3	86.3	85.4	**94.5**

IV. DISCUSSION

Now when a unbalance occurs on the supply voltage side, it also gets reflected upon the three phase load current. In original PQ method these values of unbalanced voltage and current are used for the generation of required reference currents which thereby continues reflecting the unbalance on the supply current as well. This is because the cause of the error that is unbalance in the supply voltage is not addressed before the calculations of required reference current. Therefore the error persists even in the output result that is the compensated supply current. However if the unbalance in supply voltage is eliminated by performing certain mathematical operation on the acquired voltage data before power and reference current calculations, then the effect of the error is not reflected back on the supply current. The compensated supply current is hence in phase with the supply voltage and consists of THD percentage much below than the limit of 5%.

V. CONCLUSION

The present study puts forth an improved version of instantaneous PQ theory method of reference current generation for SAPF. The proposed improvement enables the original PQ theory method to compensate and restrict the supply current and supply voltage harmonics within the standards of IEEE 519. Additionally, a comparative study of this method with other commonly used DQ method of reference current generation and its recent modified version
also validates the better functionality of this new improved instantaneous PQ theory method that can be used for reference current generation for shunt active power filters.

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