

Comparative analysis of Modified Recursive Gauss-Newton and Synchronous Reference Frame Theory

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Abstract: In the recent years of development, the abundant use of power electronics based components and systems have made a major impact on power quality of electric power supply of distribution system and raised various power quality issues. There are various technologies used for mitigation of power quality related problems. One of them is shunt active power filter (SAPF). A modified harmonic detection method based on Gauss-Newton method is used for three phase three wire shunt active power filter. The main objective of this method is to compensate for load harmonic current. A model of three-phase three wire SAPF based on the proposed modified recursive Gauss-Newton method is developed using MATLAB/Simulink. Synchronous Reference Frame theory [SRFT] is a well-known reference current generation technique, used for mitigation of harmonics. Both the reference generation method is implemented in MATLAB/Simulink and their performance comparison has been discussed.

Index Terms- Shunt active power filter (SAPF), Gauss-Newton method, Synchronous Reference Frame Theory, Hysteresis current controller band (HBCC)

I. INTRODUCTION

Three-phase, three-wire systems are prone to various power quality (PQ) issues such as load unbalancing, poor power factor, harmonics and the problem of neutral current because of the abundant use of non-linear load such as AC drives, DC drives, induction motors, UPS systems, SMPS, electronic ballasts etc. [1,2] Harmonics which are multiple of fundamental frequency have harmful effects in power system. Due to the flow of harmonics in the power system, the quality of power degrades and leads to misoperation of end-user equipment [3]. The effective RMS current increases which result in increased line losses. Other side effects of harmonics are overloads, vibration and premature aging of the generators, transformers and motors and increase in the noise level etc. There are various technologies used for mitigation of power quality related problems like a passive filter, active filter, DSTATCOM, UPQC, etc. [4,5]. Passive filters which consist of components resistors, coil/inductors and capacitors have advantages such as easy design, reliability, high efficiency, cheap. However, they suffer from disadvantages such as large size, fixed compensation ability, resonance and tuning problems [7]. On the other hand, active filters is emerging as a better solution to power quality problems because of their lower size, faster response and ability to compensate reactive power as well as harmonics [8,9]. DSTATCOM possesses many advantages like they have good filtering characteristic, better voltage regulation, harmonic elimination and reactive power compensation, etc. DSTATCOM is also a cost-effective technology [10,11]. The various control algorithm can be used for DSTATCOM to harmonic reduction, reactive power compensation, neutral current compensation, load balancing etc. [12]. Like DSTATCOM, shunt active power filter is also used for mitigation of various power quality problems discussed above. Unified Power Quality Compensator is another topology that can be used in the distribution system for power quality improvement but the cost associated with UPQC installation is very high [13]. Control algorithms which are used for above-discussed topology are the main feature of any method for compensation of PQ problems. The paper [14], deals with comparative analysis of three reference current generation techniques using Instantaneous Reactive Power Theory (P-Q), Synchronous Reference Frame Theory (D-Q) and DFT control algorithms. The paper [15] discusses the use of Synchronous Reference Frame Theory (SRFT) for power quality improvement using DSTATCOM and SAPF.

Modern techniques like least mean square (LMS) algorithms are getting popular nowadays and several modified methods of LMS. The basic principle of LMS technique is to reduce the square of the error between the reference and actual signal. There are different fixed step as well as variable step LMS techniques. The main problem associated with LMS algorithms is a selection of proper learning rate. Its convergence rate depends on the selection of proper learning rate. If it is not selected properly its performance deteriorates. [16]. This paper deals with control algorithm based on Gauss-Newton technique and SRFT method. This paper discusses the formulation of Gauss-Newton methods and its mathematical formulation for modified Gauss-Newton method (MRGN). The Gauss-Newton method is a modification of Newton method. The control algorithm is implemented using MATLAB/Simulink and performance study has been carried out. By the means of shunt active power filter, complete regulation of power system in terms of voltage stability, reactive power compensation can be achieved

II. MATHEMATICAL FORMULATION

2.1 Gauss-Newton Method

A Gauss-Newton is an iterative algorithm that can be used to solve linear as well as non-linear least square problems. Carl Friedrich in 17th century proposed a method of the least mean square in which square of the error between the reference signal and actual signal is minimized and Isaac Newton developed a method of finding the minimum of a function [17].

2.2 Calculations of Parameters

In this section, a detailed mathematical analysis of recursive Gauss-Newton method and its simplified version is discussed. A sinusoidal current in the power system can be represented as follow:

$$i_n = A_n \sin(\omega_n t + \bar{a}_n) + \epsilon_n \tag{1}$$

Where i_n is the instantaneous value of current, A_n is the peak magnitude of the current, ω_n is the frequency, \bar{a}_n is the phase shift and ϵ_n is the zero mean white noise and n is the order of harmonic. For a non-linear system, the current signal is composed of fundamental and harmonics. The determination of magnitude (A_n) and phase (\bar{a}_n) of particular harmonic current requires an equation error model. Assuming the unknown parameter matrix for the fundamental component of current being $\hat{\alpha}(k) = [A(k) \quad \bar{a}(k)]^T$, where $A(k)$ and $\bar{a}(k)$ are the magnitude and phase of fundamental component of current at k^{th} instant. The unknown parameter matrix at the $(k-1)^{\text{th}}$ instant is depicted as:

$$\hat{\alpha}(k-1) \tag{2}$$

the equation error model using (1) is described as:

$$\hat{\alpha}(k) = \hat{\alpha}(k-1) + \Delta \hat{\alpha}(k) \tag{3}$$

where $\hat{\alpha}(k)$ is an error at a k^{th} instant, $i(k)$ is total current at a k^{th} instant. A standard procedure to obtain a solution for

is using method of modified LSs in which following cost function, E_N is minimized.

$$E_N = \sum_{k=1}^N \lambda^{N-k} \epsilon^2(k) \tag{4}$$

Where E_N is exponentially weighted cost function, λ is forgetting factor, whose value is in between (0, 1). The minimization of the cost function is a non-linear function for which GN method is followed.

Taking derivative of equation (1) w.r.t. (2) we arrive at following equation

$$\frac{\partial i(k)}{\partial \hat{\alpha}(k)} = \omega_n A(k) \cos(\omega_n t + \bar{a}(k)) \tag{5}$$

Rearranging (5) and comparing it with equation (3) we get the error signal as

$$\epsilon(k) = i(k) - \hat{\alpha}(k) \frac{\partial i(k)}{\partial \hat{\alpha}(k)} \tag{6}$$

Taking partial derivative of above equation(6) w.r.t. $\hat{\alpha}(k)$ and defining gradient as

$$Y(k) = - \frac{\partial \epsilon(k)}{\partial \hat{\alpha}(k)} \tag{7}$$

Where $Y(k)$ is gradient

Putting the value of $\hat{\alpha}(k)$ in (3) from (10)

$$\epsilon(k) = \hat{\alpha}(k) Y(k) \tag{8}$$

using standard LS method, solution to above equation is

$$\hat{\alpha}(k) = (Y^T(k) Y(k))^{-1} Y^T(k) \epsilon(k) \tag{9}$$

where,

$$H(k) = \sum_{j=1}^k Y(j) Y^T(j) \tag{10}$$

is called Hessian matrix

The updating equation for estimation of

is written as,

$$\hat{\alpha}(k) = H(k)^{-1} Y^T(k) \epsilon(k) \tag{11}$$

$$Y(k) \hat{\alpha}(k) \tag{12}$$

and updating equation for $H(k)$ is given by modifying (13)

$$H(k) = H(k-1) + Y(k) Y^T(k) \tag{13}$$

Equations (12) and (13) are updated recursively so as to minimize the error

2.3 MODIFIED RECURSIVE GAUSS-NEWTON METHOD

The Recursive Gauss-Newton (RGN) method is quite a complex method and it requires more memory for repetitive calculations using (11)– (13) are very large. An RGN method is simplified to obtain Modified Recursive Gauss-Newton (MRGN) method can only be realized in the real system after appropriate simplifications and this section gives the detailed mathematical analysis of MRGN algorithm. From (2), (7), $Y(k)$ is calculated as

$$Y(k) = \begin{bmatrix} \dots \\ \dots \\ \dots \end{bmatrix} \quad (14)$$

$$Y(k) = [-\sin(n + \hat{a}(k-1))] \quad (15)$$

$$H(k) = \sum_{n=1}^N a^{2n} [\sin(n + \hat{a}(k-1)) - (k-1)\cos(n + \hat{a}(k-1))]^T \quad (16)$$

Using $\frac{d}{dx} \sin(x) = \cos(x)$ and $\frac{d}{dx} \cos(x) = -\sin(x)$

$$H(k) = - \begin{bmatrix} 2a^2 \cos(n + \hat{a}(k-1)) \\ \dots \\ \dots \end{bmatrix} \quad (17)$$

$$H(k) = - \begin{bmatrix} 2a^2 \cos(n + \hat{a}(k-1)) \\ \dots \\ \dots \end{bmatrix} \quad (18)$$

Defining $C(N) = \frac{1}{2a^2}$ as a constant term from (17) the inverse of Hessian matrix is calculated as

$$H^{-1}(k) = \begin{bmatrix} \frac{1}{2a^2} & & \\ & \dots & \\ & & \dots \end{bmatrix} \quad (19)$$

Putting the value of $H^{-1}(k)$ from (18) in (12), and writing the updating equation for (k)

$$Y^T(k) \hat{a}(k) \quad (20)$$

$$\hat{a}(k) \quad (21)$$

Also from (13)

$$\frac{1}{2a^2} [-\sin(n + \hat{a}(k-1))] \quad (22)$$

$$\sin(n + \hat{a}(k-1)) \hat{a}(k) \quad (23)$$

$$\hat{a}(k) = \hat{a}(k-1) + \frac{1}{2a^2} \cos(n + \hat{a}(k-1)) \hat{a}(k) \quad (24)$$

Finally, equations (23) and (24) are implemented in MATLAB/Simulink with moving average filters and its accuracy is checked by comparing it to the FFT block present in the MATLAB/Simulink library Modified RGN (MGRN) method is fairly less complex when compared with the original method. This method is now applied to estimate the fundamental component of current in three-phase, three-wire distribution system.

III. SYSTEM DESCRIPTION

3.1 Shunt Active Power Filter

Three-phase active filters are used for high power nonlinear loads such as adjustable speed drive (ASD) and AC to DC converters. Fig.1 shows the basic block diagram of shunt active power filter. It consists of voltage source inverter (VSI) with a capacitor across it. The voltage across the capacitor is defined as dc-link voltage; the dc-link voltage is kept constant for proper operation of the filter. At the point of common coupling (PCC), filter, non-linear load, and the source is connected. The gating

pulses generated by the control block are given to the inverter. The dc-link voltage, load current, and source voltage are sensed through sensor unit and provided to the control block for generating the firing pulses.

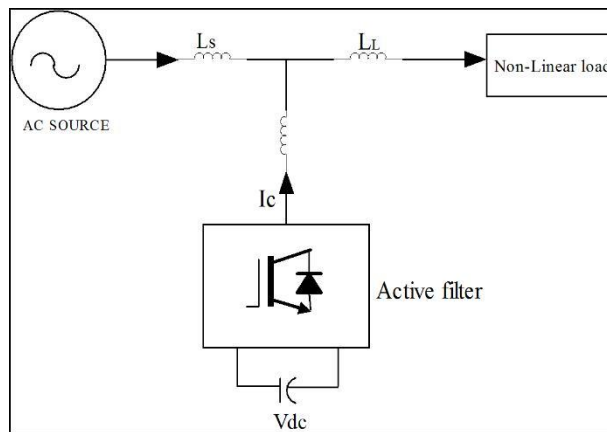


Figure 1 Block diagram of shunt active power filter

There are various methods of generating compensating harmonic current in SAPF increase the performance of the system by eliminating current harmonics present in the load current. The SAPF with on voltage source inverter is commonly used topology because of its efficiency. Active filter can be used as shunt active filter or combination of both. This paper mainly discusses the working of shunt active power filter.

3.2 Working of SAPF:

The Shunt Active Power Filter is connected in parallel with the transmission line through the coupling inductors. Its power circuit composed of a three-phase three-leg voltage source inverter with a DC link capacitor. The function of an active power filter is to generate a compensating current with 180-degree phase opposition and injects it back at the point of common coupling so the effect of the current harmonics introduced by the nonlinear load is eliminated. This will thus reduce the harmonic content present in the line and make the current waveform more sinusoidal. So the working process of SAPF can be divided into 3 main parts as:

1. Identifying the harmonic component present in the line current,
2. Generating the reference current
3. Providing the switching pulses for the inverter circuit, generating a compensating/filter current and injecting it back to the line.

IV. SYNCHRONOUS REFERENCE FRAME THEORY

The control algorithm adopted for the active filter is the vital part of the filter which greatly affects its performance. Synchronous Reference Frame Theory also called as (D-Q) theory is used for reference current generation. For extracting the reference currents in shunt active power filters various control strategies can be implemented v.i.z. Instantaneous Reactive Power Theory (p-q theory), Unity Power Factor method, Goertzel algorithm, One Cycle Control, Fast Fourier Technique, sliding mode control and synchronous reference frame theory (D-Q theory) etc. Fig.2 shows the block diagram of the algorithm for three-phase SRF-theory. After line currents are detected a reference current signal is generated. The SRFT (D-Q) block is used for harmonic component extraction. In SRF theory Park transformation is used.

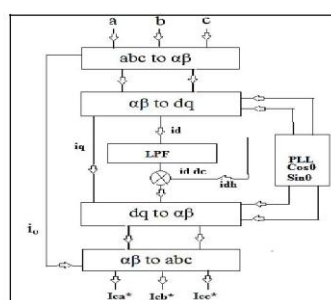


Figure2. Block diagram of SRF based algorithm

In this method, load currents are first converted into the d-q components in order to separate out the fundamental and harmonics components of instantaneous currents (i_d , i_q). The source currents (i_a , i_b , i_c) are first detected and then converted into two-phase stationary frame ($\hat{a}\hat{b}$ -0) from the three-phase stationary frame (a-b-c), with following equation.



Now, the two phase current quantities i_{α} and i_{β} of stationary $\alpha\beta$ -axes are transformed into two-phase synchronous frame (d-q-axes) using equation (25), where $\cos\theta$ and $\sin\theta$ are the synchronous unit vectors which can be generated using phase-locked loop system (PLL).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \tag{26}$$

The d-axis current and q-axis current are combination of DC and AC parts i.e. fundamental current (i_{dc}) and the load harmonic current (i_{lh}). This harmonics components can be eliminated by using a LPF. In the synchronous reference frame (rotating frame) the q-axis current (i_q) represents the sum of the fundamental component of reactive load currents and part of the load harmonic currents. So for calculation of reference compensation current, the q-axis current can be utilized totally. Inverse parks transformation is done by following equation:

$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{27}$$

Finally, the transformation from two-phase to three-phase stationary is carried out i.e. from $\alpha\beta 0$ to abc as per equation (27) and the compensation reference currents i_{ra}^* , i_{rb}^* and i_{rc}^* are obtained.

$$\begin{bmatrix} i_{ra}^* \\ i_{rb}^* \\ i_{rc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ i_0 \end{bmatrix} \tag{28}$$

The reference signal i_{abc}^* is produced from SRF algorithm is compared with actual current signal from which error signal is developed which is fed to the hysteresis band current control. The HBCC produce pulse signals for necessary operation of SAPF. The results obtained with SRFT method also provides satisfactory operation of SAPF. But in SRFT method various transformation are involved i.e. abc- $\alpha 0$, $\alpha 0$ -dq, dq- $\alpha 0$ and finally $\alpha 0$ -abc which is complex. These drawbacks of SRFT method is eliminated in Gauss-Newton method.

The adverse effects of non-linear load are well known. Here, active power filter becomes the powerful tool to solve the problem related to voltage or current harmonics and also for reactive power compensation. Active power filters are connected to 3 phase AC transmission lines in order to provide voltage regulation and to reduce harmonic content present in the lines. The implementation of proposed scheme can be shown in the block diagram as follow:

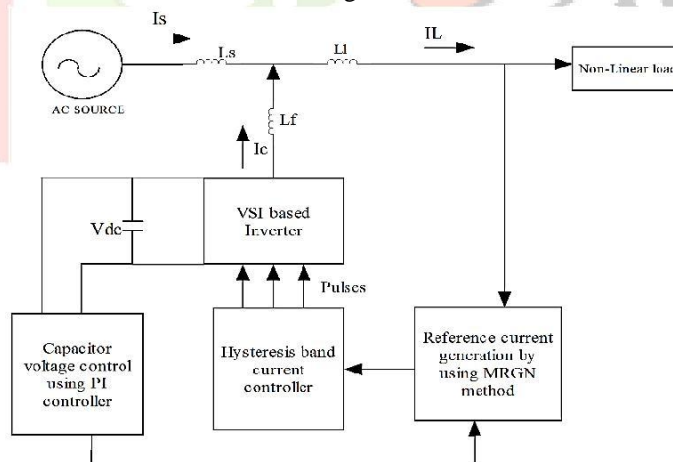


Figure 3. Basic block diagram of the proposed scheme

V.HYSTERESIS BAND CURRENT CONTROL

Various current control strategies can be employed for SRAF. The first objective of any control algorithm is to obtain sinusoidal source currents in phase with the source voltages and the second objective is the stabilization of the DC output voltage (Vdc) at a required value. Here, in this proposed work the hysteresis band current control (HBCC) technique for pulse generation in voltage controlled inverter(VSI). The HBCC method offers advantages like good stability, very fast response, and good accuracy and also it is simple in operation. Fig (4) shows the HBCC technique employed in an active power filter used for generation of switching pulses which in turn used for the control of line current.

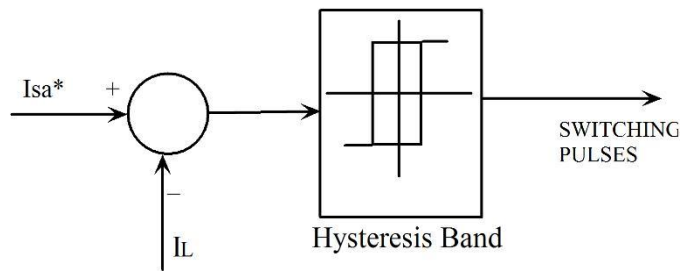


Figure 4. Hysteresis current controller band

HBCC consist of a hysteresis band surrounding the generated error current. The current error is obtained by subtracting the actual load current from the reference current. The reference current used here is obtained by the Gauss-Newton method as discussed earlier which is represented as I_{sa}^* . The actual load current is represented as I_L . The error signal is then given to the relay which consist of desired hysteresis band to obtain the switching pulses for the inverter.

The operation of APF mainly depends on the order of the pulse generated by the any controller. A particular band is set above and below the generated error signal. Whenever error signal intersects the upper band or lower band then the output voltage switches so as to decrease the input current or to increase the input current respectively. Accordingly switching pulses are generated which are then given to the inverter. Fig.5 shows the pulses generation technique.

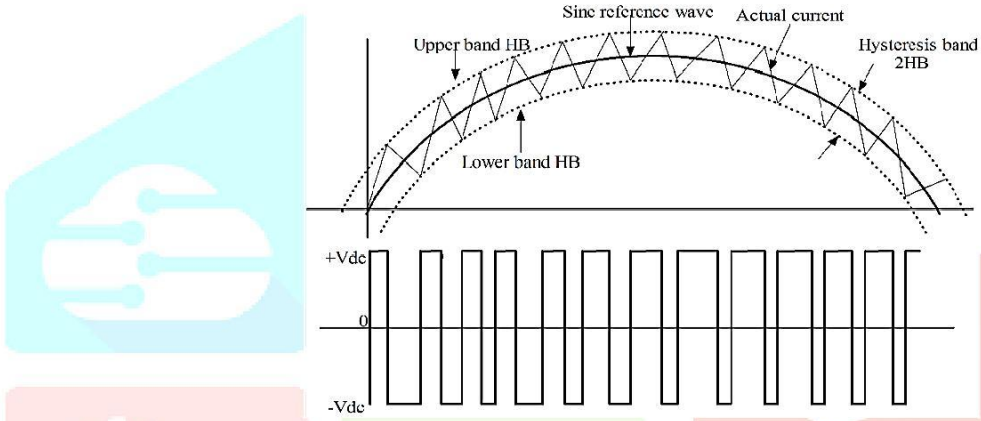


Figure 5. HBCC pulse generation

VI.RESULTS AND DISCUSSION

Fig.6 shows simulation model of Modified Recursive Gauss-Newton method implemented on shunt active power filter for three-phase three-wire distribution system employed for power quality improvement.

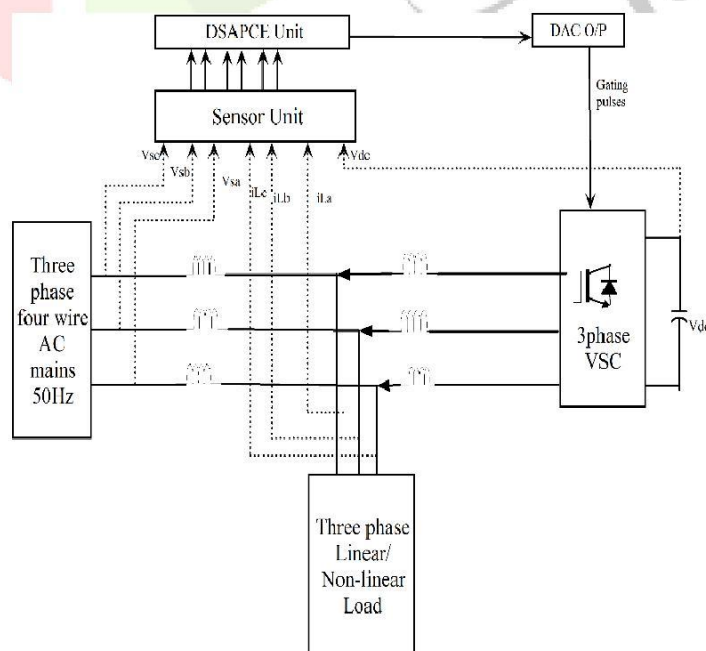


Figure 6. Simulation model of proposed work

The results obtained from given simulation model are shown in the following figures. Proposed MRGN technique model is realized in MATLAB/Simulink and simulated for the analysis of system behavior under non-linear load.

Table 6.1 SYSTEM PARAMETERS

Parameter	Notation	Value
Source voltage	V_s	380
Source Frequency	f	50Hz
SAPF Line Inductance	L, L_2, L_3	3.5mH
Filter Resistance	R_f	10Ω
Filter Capacitance	C_f	15μF
DC Capacitor voltage	V_{dc}	700 V

6.1 Results obtained with MRGN method

The load current is non-linear in nature because of rectifier based non-linear load with the magnitude of 55A and source side current is nearly linear with the magnitude of 56.93A fig.7 and fig.8.

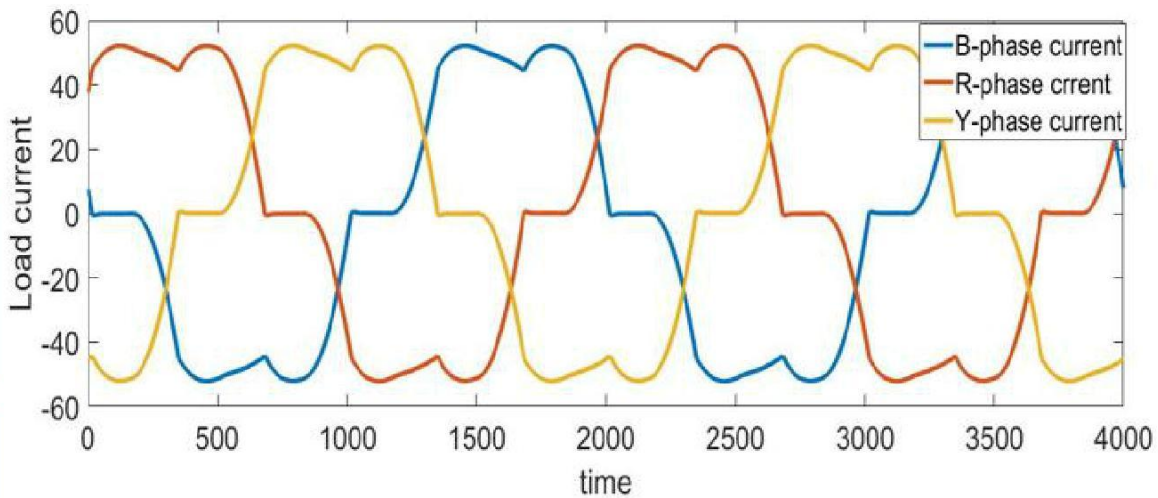


Figure 7. Load current waveform

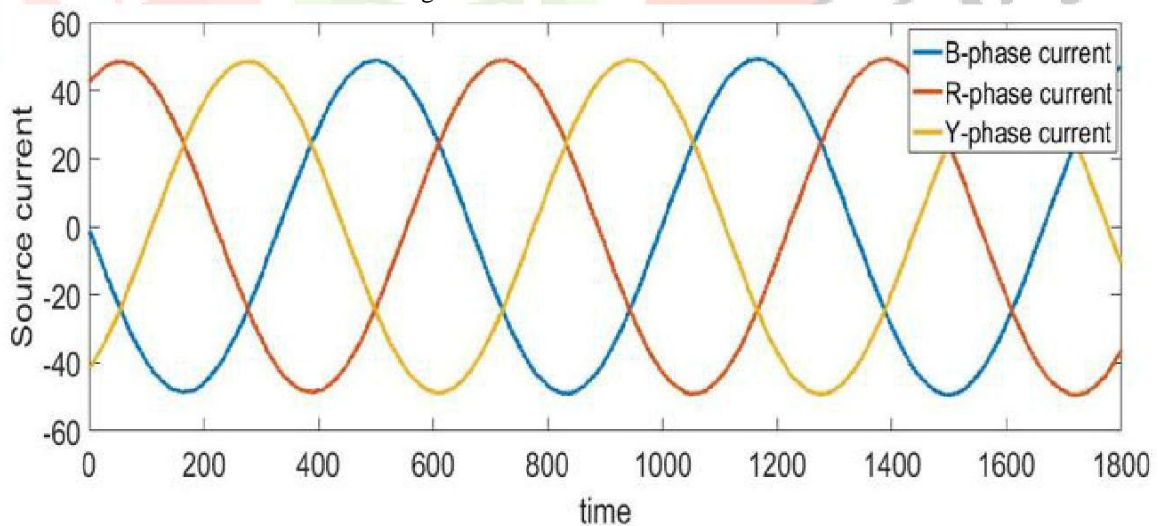


Figure 8. Source current waveform

fig.7 and fig.8 shows the results obtained from MRGN method. The FFT analysis of shows load current has total harmonic distortion (THD) value of 24.13%, and the source current has THD of 2.53%. The supply current is sinusoidal having THD substantially below the IEEE 519 limits.

The capacitor voltage across inverter is maintained constant at nearly 700V with the help of PI controller in MRGN method.

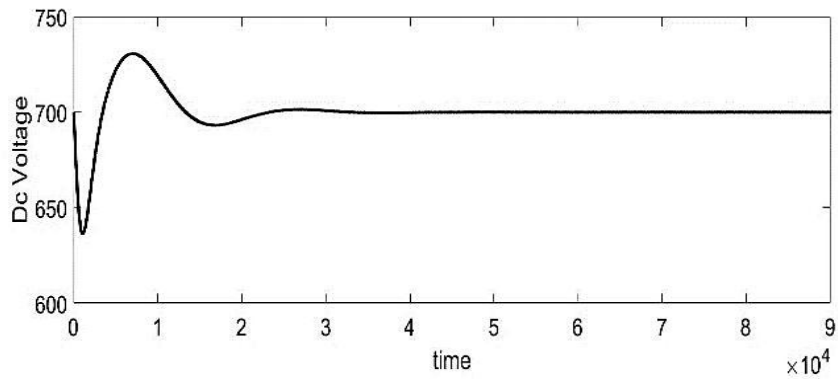


Figure 9.DC link capacitor voltage

6.2 Comparison with SRFT theory

With same parameters discussed above, the simulation is carried with Synchronous Reference Frame Theory(D-Q) and results obtained are as follows: The load current is non-linear in nature with the magnitude of 56A and source side current is nearly linear with the magnitude of 56.6A fig.10 and fig.11

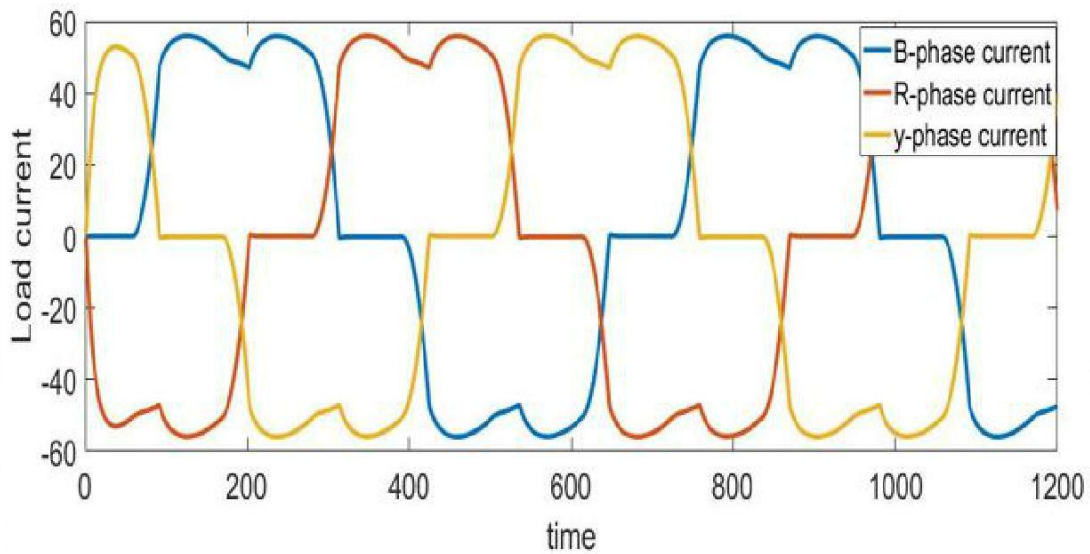


Figure 10. Load current waveform

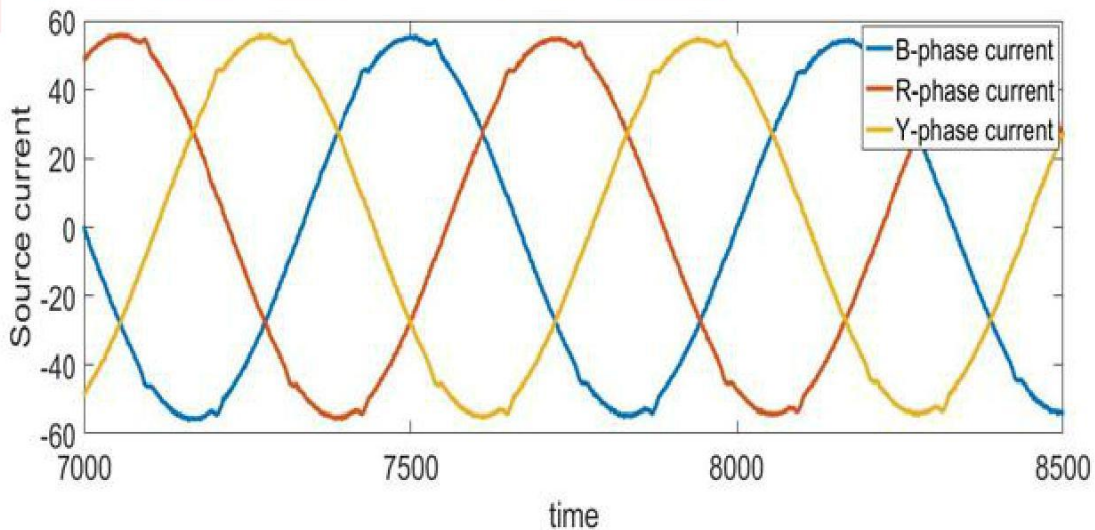


Figure 11. Source Current Waveform

The FFT analysis of above fig.10 and fig.11 show the total harmonic distortion (THD) content in load current is 25.12% which is reduced to 1.78% of source current achieving IEEE 519 limits. The capacitor voltage across inverter is also maintained constant with SRFT method at nearly 700V.

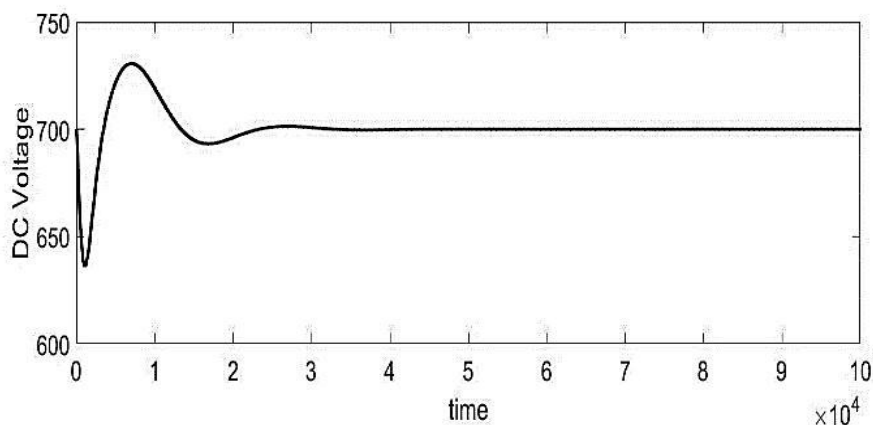


Figure 8. DC link capacitor voltage

Both methods give satisfactory results with THD below 5% and improving the quality of power. Also DC link voltage is maintained constant for proper operation of inverter.

VII. CONCLUSION

The proposed work describes compensation process for the line current harmonics generated due to nonlinear loads in the system. Using Modified Recursive Gauss-Newton Algorithm (MRGN) and Synchronous Reference Frame Theory (SRFT) three-phase reference current signal is generated, this is compared with the actual load current. The resultant signal is then provided to the HBCC. Finally, HBCC provides gating pulses to three-phase voltage source inverter. HBCC technique used for the switching pulse generation is found more effective and gives a fast response. The line compensation achieved with both the methods is within the acceptable limits. The new proposed MRGN technique is quite simple and fast and can be applied for achieving load compensation using SAPF.

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