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Enhancement of grid-tied wind system performance under different loading scenarios

B. Nagi Reddy[1*], *V. Naveen*[2]

[1]Associate professor, Vignana Bharathi institute of technology, Hyderabad, India
[2]PG scholar, Vignana Bharathi institute of technology, Hyderabad, India

Abstract. In this paper, a grid-tied wind system with three-phase and four wire is planned to operate under a variety of loading circumstances. It is proposed that a control technique be utilized in order to provide a reference current signal for the purpose of managing the operation of a three-phase four-wire parallel connected active power filter. When it comes to the generation of reference current, the synchronous reference frame (SRF) method based on time-domain has been widely acknowledged to come with the advantage of providing control simplicity. The parallel active power filter, also known as SAPF, is the most efficient method for reducing the effects of current harmonics. For example, the SRF approach, which was initially designed to function with a three-wire system, cannot be immediately used to a four-wire network without undergoing adjustments. As a result, a new topology is projected in order to accomplish the minimization of harmonic current under non-linear, step change, and/or unbalanced loads. Through the utilization of the MATLAB/Simulink software, the design structure of the proposed approach was developed.

1 Introduction

Ensuring that the amount of harmonics distortion in the power supply remains below the acceptable limit, as specified by the IEEE standard 519, has developed increasingly difficult because of the quick progress of power converter technologies [1]. This progress has led to a substantial growth of nonlinear loads in use of many appliances. During process, nonlinear loads have the habit to produce harmonic currents that degrade the power quality of the structure, as evidenced by a high total harmonic distortion (THD) worth. This also reduces the overall efficiency of the system, as indicated by a low power factor. Additionally, the excessive heat generated by these loads can lead to the failure of other associated equipment [2].

Therefore, it is now obligatory to take measures to reduce the detrimental impact of these harmonic currents and effectively limit them to a tolerable level. Several measures have been taken, with the most significant being the creation of parallel active power filters (PAPFs). These filters are acknowledged as an operative solution for addressing issues instigated by harmonic currents [3]. During process, a standard PAPF will initially assess the components of harmonic of the structure that is contaminated with harmonics. Using this assessment, the PAPF will produce counteractive current, similarly referred to as extenuation current, which is then feed back into the electric network. This corrective current effectively cancels out the inventive harmonic currents present in the electric network. It is crucial to highlight that the minimization procedure is deemed effective once the source current is capable of restoring the fundamental sinusoidal shape with a THD value of 5% or less [1].

Additionally, it should be operating in-phase and exhibiting the equivalent essential frequency as the functioning source voltage. Regardless of the reliability of PAPF, it is essential to have a well-designed control system in order for it to function effectively. This control system typically includes several phases such as extracting harmonic contents, controlling the dc-link voltage, synchronizing with the power system's operation, and generating control pulses. Out of all the control phases, the extraction of harmonic contents is the initial and crucial phase to be carried out, as acknowledged in references [4].

Therefore, it is essential to possess accurate harmonics data of the power system in order to effectively carry out the remaining control phases. Currently, there are numerous existing strategies and attempts have been made to categorize them based on learning methodologies, time-domain, and frequency-domain [5]–[7]. However, time-domain techniques, such as the instantaneous power (pq) theory, and synchronous reference frame (SRF) are still widely used due to their recognized advantage of having a simple control structure. Nevertheless, their control systems exhibit a high level of inflexibility, hence restraining their ability to be directly realized in various electrical circuit topologies. For example, the SRF approach,

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[*] Corresponding author: nagireddy208@gmail.com

originally designed for use by three-phase networks, can't be easily adapted to single-phase systems without significant modifications to the general regulator assembly. The reason for this is that the SRF approach operates in αβ and dq coordinates, which cannot be achieved using a single-phase waveform alone. Therefore, appropriate for the SRF thought to be applicable to a single-phase system, it is necessary to have a method for converting a single-phase waveform into αβ coordinates. An intriguing approach to examine this phenomenon has been documented in [8], [9], where noticeable and extensive alterations may be easily discerned. In addition, the majority of the current studies on SRF approaches rely on the use of a numerical low-pass filter (LPF), [10]–[13].

An inherent challenge associated with numerical filters is the requirement for meticulous tuning in order to achieve the desired performance. Furthermore, often a phase-locked loop (PLL), all SRF approaches require supplementary assistance from a synchronizer, which has the potential to complicate the structure of the complete control structure. Therefore, control technique be utilized in order to provide a reference current signal for the purpose of managing the operation of a three-phase four-wire shunt connected active power filter. When it comes to the generation of reference current, the time based SRF method has been widely acknowledged to come with the advantage of providing controller ease. The parallel active power filter, also known as PAPF, is the most efficient method for reducing the effects of current harmonics. The MATLAB/Simulink package is employed to develop an extensive model of a three-phase four-wire PAPF system circuit, encompassing its control strategies. This model is subsequently used for rigorous testing and analysed to confirm the strategy thought of the projected method. The testing is carried out in two modes: steady-state and transient-state. It accounts for imbalanced and distorted grids and uses two distinct kinds of nonlinear rectifier loads. To further emphasize the advantages of the suggested method, a comparison is made under same circumstances utilizing the conventional SRF technique.

2 Proposed wind connected PAPF system

At the point of common connection (PCC), an active power filter (APF) is depicted in Figure 1. This APF is linked in parallel to a three-phase four-wire power system. Positioning the Power Active Power Filter (PAPF) between the supply grid and the nonlinear load, which is often a bridge rectifier and is responsible for the generation of harmonics, is done with the intention of enhancing the power quality of the grid. This study employs a conventional three-phase VSI as the active filter. As shown in Figure 1, the outcome of the active filter is often associated to the output inductive filter to reduce switching ripples generated by the active filter, which is necessary to generate an accurate mitigation current, denoted as i_{Mabc}. It is important to note that when the PAPF produces i_{Mabc}, a small current, i_{dcabc}, must be extracted to continue a consistent voltage of the dc-link capacitor, ensuring the stable generation of i_{Mabc}.

The regulator of a distinctive PAPF consists of several interconnected control stages, as described in the previous section. Each regulating stage is renamed as a controller section, as shown in Figure 2. This work focuses specifically on the reference current production part, which includes the procedures for synchronization and harmonic extraction. The proposed method in this module is the modular-FED approach. The dc-link voltage control of capacitor and gating pulse generation sections utilize the standard PI regulator and a conventional sinusoidal pulse-width modulation (PWM) method respectively. Both methods are widely used and are known for their effectiveness in handling simple control structures.

During operation, the load current i_{Labc} is analysed by the current dispensation section within the required current generating element to identify the harmonic components. Concurrently, the dc-link capacitor voltage control module analyses the instantaneous dc-link voltage, V_{dc}, to ascertain the correct charging current, I_{dc}. Furthermore, the reference current generation module's voltage processing section turns the source voltage v_{Sabc} into a sine wave synchronization signal. It is possible to determine the synchronized reference current signal i^*_{Sabc} by utilizing the extracted harmonic substance, the projected I_{dc} value, and the synchronization sine function. Establishing a feedback loop by comparing the estimated supply current i_{Sabc} with the required reference current i^*_{Sabc} ensures constant operation of the PAPF. Minimizing errors is achieved by generating the required switching pulses to regulate the performance of the PAPF.

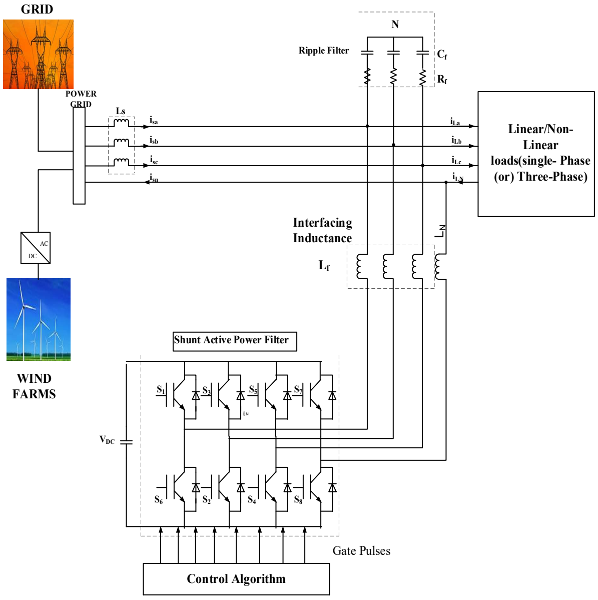

Fig.1. Three-phase four-wire Wind energy system with PAPF

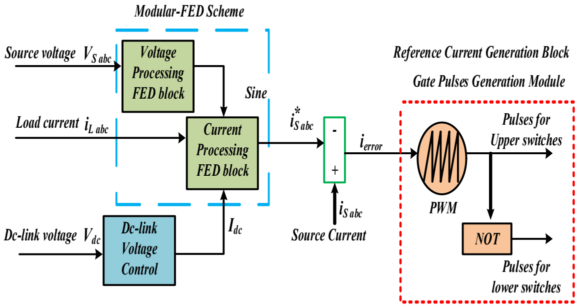

Fig.2. Control organization of the proposed system

3 SRF Method for Single – Phase & Three – Phase Systems

The present part provides an overview of the working operation of the SRF method, focusing on the procedure of generating the required reference current waveform. It also compares the control structure differences between the SRF methodology developed for three-phase and single-phase purposes.

The SRF method is specifically calculated for three-phase systems and involves the utilization of Park and Clarke transformations to facilitate coordinate transformations, namely between αβ, abc, & dq axes. The expressions provided in equations (1) & (2) are the crucial matrices used for conducting forward coordinate transformations. These transformations involve converting coordinates from abc to αβ ($\boldsymbol{T_{\alpha B}^{abc}}$) and subsequently from αβ to dq ($\boldsymbol{T_{dq}^{\alpha B}}$) coordinates. However, equations (3) and (4) provide the essential matrices used for the inverse transformation of coordinates. Specifically, they convert coordinates from dq to αβ ($\boldsymbol{T_{\alpha B}^{dq}}$) and subsequently from αβ back to abc ($\boldsymbol{T_{abc}^{\alpha B}}$) coordinates. It is important to understand that in equation (2) and (3), sin(ωt) & cos(ωt) reflect the synchronization position functions that are typically provided by a Phase-Locked Loop (PLL).

$$T_{\alpha\beta}^{abc}=\frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix} \qquad (1)$$

$$T_{dq}^{\alpha\beta}=\begin{bmatrix}\sin(\omega t) & \cos(\omega t)\\ -\cos(\omega t) & \sin(\omega t)\end{bmatrix} \qquad (2)$$

$$T_{\alpha\beta}^{dq}=\begin{bmatrix}\sin(\omega t) & -\cos(\omega t)\\ \cos(\omega t) & \sin(\omega t)\end{bmatrix} \qquad (3)$$

$$T_{abc}^{\alpha\beta}=\begin{bmatrix}1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix} \qquad (4)$$

Figure 3 displays the regulator layout of a standard SRF method used in the proposed, four-wire structure. The following steps show how (1) & (2) equations used to change the estimated output current i_{Labc} in abc-axes into its matching depiction in dq-axes, which is i_{Ldq}.

$$\begin{bmatrix}i_{L\alpha}\\ i_{L\beta}\end{bmatrix}=T_{\alpha\beta}^{abc}\begin{bmatrix}i_{La}\\ i_{Lb}\\ i_{Lc}\end{bmatrix} \qquad (5)$$

$$\begin{bmatrix}i_{Ld}\\ i_{Lq}\end{bmatrix}=T_{dq}^{\alpha\beta}\begin{bmatrix}i_{L\alpha}\\ i_{L\beta}\end{bmatrix} \qquad (6)$$

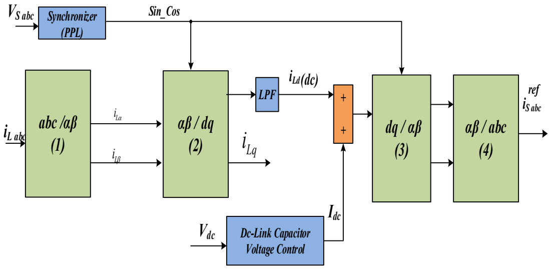

Fig.3. Control scheme of SRF system for three-phase systems [12], [21].

When expressed in dq-coordinates, the output current i_{Ldq}, which is affected by harmonic distortion, would appear as a direct current signal with periodic fluctuations. More precisely, the primary component of the output current will consist of a constant direct current signal, while the additional components will manifest as fluctuations known as ripples. Consequently, the subsequent relationship can be expressed as

$$\begin{bmatrix}i_{Ld}\\ i_{Lq}\end{bmatrix}=\begin{bmatrix}i_{Ld(dc)}+i_{Ld(ac)}\\ i_{Lq(dc)}+\ i_{Lq(ac)}\end{bmatrix} \qquad (7)$$

where $i_{Ld(dc)}$ and $i_{Ld(ac)}$ are the basic and harmonic parts of the output current in the d-coordinate, correspondingly. The q-coordinate is also shown in a similar way. You can easily get the basic part of the load current, $i_{Ld(dc)}$, by using an LPF. Then, you can use I_{dc}, which is calculated by the voltage control module (PI regulator) of dc-link capacitor, to get the reference current signal you want. It's essential to know that q-coordinates don't have a big impact on the reference current signal that you want, so you can ignore them [23]. I_{dc} and $i_{Ld(dc)}$ together make up the intended reference signal's value in dq-axes. This signal can be changed to $\alpha\beta$ axes as $i_{L\alpha\beta}^{ref}$ and then reverse to abc-axes as i_{Sabc}^{ref} by following these steps.

$$\begin{bmatrix}i_{L\alpha}^{ref}\\ i_{L\beta}^{ref}\end{bmatrix}=T_{\alpha\beta}^{dq}\begin{bmatrix}(i_{Ld(dc)}+i_{Ld})\\ 0\end{bmatrix} \qquad (8)$$

$$\begin{bmatrix}i_{Sa}^{ref}\\ i_{\ Sb}^{ref}\\ i_{Sc}^{ref}\end{bmatrix}=T_{abc}^{\alpha\beta}\begin{bmatrix}i_{L\alpha}^{ref}\\ i_{L\beta}^{ref}\end{bmatrix} \qquad (9)$$

Figure 4 depicts a noteworthy control assembly of an SRF approach that has been documented to be effective in single-phase systems. As stated in part I, in order to use the technique of single-phase application, modifications must be made to the original three-phase SRF approach. The primary adjustment required is the method of converting the axes of the observed output current to its corresponding depiction in Figures 3 and 4. It is evident from Figures 3 and 4 is that matrices (1) and (4), primary Clarke transformation equations are not applicable to single-phase systems. Therefore, appropriate for the SRF concept to be applicable in single-phase applications, it is necessary to have a method to transform a single-phase signal into αβ-axes, and conversely. Put simply, it is necessary to find a method to substitute the transformation vectors (1) and (4).

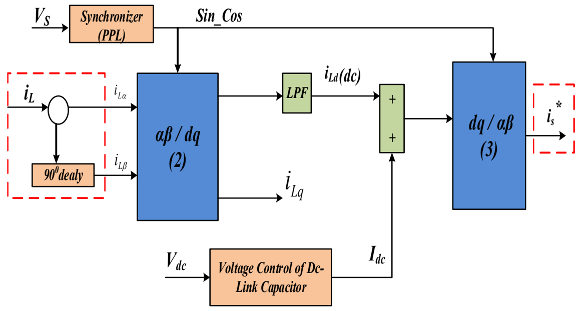

Fig.4. Single-phase Control assembly of SRF method [15], [19].

An intriguing method for achieving forward transformation involves announcing a 90^0 shift in phase to the initial single-phase indication, so creating an imaginary sign. Following that, the first signal will be the α-coordinate and the imagined signal will be the β-axis. In terms of math, the forward translation steps can be put together in this way:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} i_{L(\omega t)} \\ i_{(\omega t+9\ \circ)} \end{bmatrix} \tag{10}$$

The function $i_{L(\omega t)}$ indicates the estimated single-phase output current which is denoted as $i_{L\alpha}$. The function $i_{L(\omega t+90^\circ)}$ denotes the estimated output current of single-phase, behind by 90◦ or a 1/4th duration, which is denoted as $i_{L\beta}$. By utilizing the waveforms present in αβ-axes, it is possible to perform operations (6), (7), and (8) in order to derive the appropriate estimated signal in αβ-axes, denoted as $i_{\alpha B}^{ref}$. Put simply, the control operations carried out in dq-coordinates are applicable to both single-phase and three-phase SRF approaches.

Conversely, for the opposite conversion, just the α-axis is required as it is the sole actual sign of the organization, while the β-axis is an unreal sign included solely to satisfy the thought of the stationary reference frame (SRF). Therefore, based on equation (8), just the component $i_{L\alpha}^{ref}$ will be considered and it may be directly regarded as the reference current signal i_s^{ref} for the single-phase system, as expressed mathematically below.

$$i_S^{ref} = i_{L\alpha}^{ref} = sin(\omega t) \times (i_{Ld(dc)} + i_{Ld}) \tag{11}$$

In summary, this part has compared the operational principles of single-phase and three-phase SRF approaches. The objective of this comparison is to elucidate the necessary modifications required to adapt a conventional three-phase SRF technology for utilization in a single-phase system. The primary adjustment required is to identify other methodologies that can substitute the utilization of the Clarke-matrix. Completing this task is not as straightforward as previously stated, since it requires a comprehensive grasp of the signal properties in αβ-axes. Although there are variances, two resemblances that may be noted are the requirements of a Phase-Locked Loop (PLL) and a Low-Pass Filter (LPF). The SRF approaches have intrinsic vulnerabilities that might potentially diminish their efficacy, and as a result, the overall performance of the complete PAPF mitigation can be affected.

4 Modular Fed Method

This part will now introduce the operational idea of the projected modular-FED method, taking into account the limitations noted in standard SRF techniques. The functioning principle of a modular FED element will be initially explained, followed by a discussion on how these distinct modular blocks can be combined to create a module for generating a three-phase reference current. Figure 5 is a schematic diagram that represents the control framework of a fundamental FED block. The primary purpose of the FED block is to extract basic elements from an alternating current signal, as suggested by its name. The extracted fundamental elements consist of two components: (1) the fundamental magnitude of the signal and (2) a sine function of the signal that operates at the fundamental frequency. The generation of reference current for a conventional PAPF requires two essential signals. In Figure 5, it is demonstrated that the FED block employs the single-phase SRF technique, which is depicted in Figure 4, in order to transform a single-phase signal x into its corresponding representation in αβ-axes (x_α and x_β). Subsequently, a highly selective filter (HSF) is employed in i-coordinates with the purpose of extracting the fundamental elements ($x_{\alpha(fd)}$ and $x_{\beta(fd)}$) of the signal. After that, these components are converted into a unity sine function that may be utilized, complete with an elementary frequency and amplitude. In its most basic form, a Heat Sink Fan (HSF) can be defined as having the following characteristics:

$$x_{\alpha(fd)} = \frac{K}{S}(x_\alpha - x_{\alpha(fd)}) + {}^{2\pi fc}/_{3}\,(x_{\beta(fd)}) \tag{12}$$

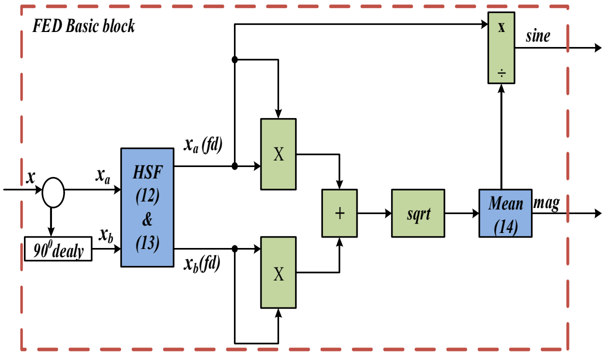

Fig.5. A simple FED block's internal control architecture

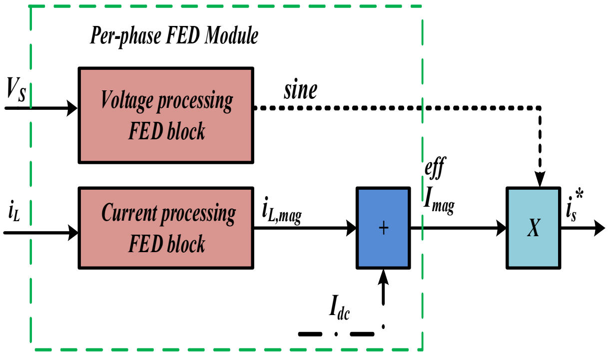

Fig.6. Per-phase module of Modular-FED method

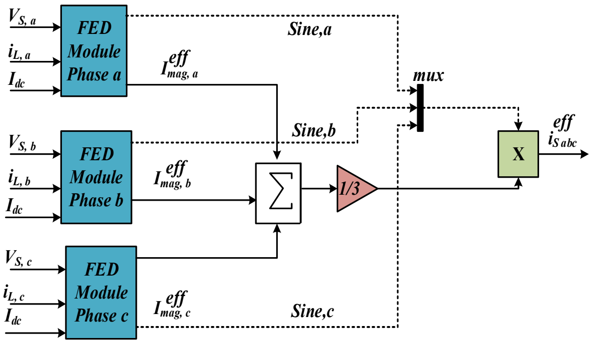

Fig.7. Proposed reference current generation unit for three-phase.

$$x_{\beta\,(fd)} = \frac{K}{S}(x_\beta - x_{\beta\,(fd)}) + {}^{2\pi fc}/_{3}\,(-x_{\alpha(fd)}) \qquad (13)$$

The constant K represents the tuning gain, whereas fc represents the cut-off frequency. An analysis has been conducted on the selectivity of HSF, and it has been observed that a smaller value of the constant K results in improved selectivity of HSF. However, this also leads to a longer time delay. In order to extract the fundamental element of an alternating current (AC) signal, a constant value, denoted as K, is usually chosen within the range of 20 to 100. The frequency of the AC signal, denoted as fc, is consistently set at 50 Hz, as stated in references [30] and [31]. Additionally, as illustrated in Figure 5, a mathematical averaging function is utilized to further minimize the fluctuations present in the retrieved basic magnitude mag as follows:

$$mag = \frac{1}{T}\int_0^T \sqrt{x^2_{\alpha(fd)} + x^2_{\beta(fd)}}\,dt \qquad (14)$$

The unity sine equation will be achieved concurrently as follows:

$$sine = sin(\omega t) = \frac{x\alpha(fd)}{mag} \qquad (15)$$

Figure 6 illustrates the internal composition of the suggested modular FED approach. Figure 6 illustrates the connection of two fundamental FED blocks to form a unified single-phase FED module. Specifically, a single FED block is employed to process the source voltage signal v_S and transform it into a useable unity sine function sine with an elementary frequency. Simultaneously, another FED block is utilized to process the load current signal i_L and extract the magnitude of the fundamental current $i_{1L,mag}$. In this study, an HSF tuning gain of K = 20 is used for voltage processing, whereas an HSF tuning gain of K = 90 is used for current processing. Afterwards, the magnitude that was extracted, along with the unity sine function and the estimated I_{dc} by the dc-link capacitor voltage control module (see Figure 3), can be used to construct the appropriate reference current signal i_s^{ref} as follows:

$$i_s^{ref} = sin(\omega t) \times I^{eff}_{mag} \qquad (16)$$

Alternatively, Fig. 7 illustrates the replication and integration of the FED per-phase module from Fig. 6 to serve as a module for generating reference current in a three-phase system. It is evident that the FED per-phase module, which functions in a single-phase system, can be directly used in a three-phase system without any alterations to its fundamental structure. Specifically, three per-phase FED modules will be required to extract the appropriate sine function and the effective magnitude of the current I^{eff}_{mag} for each phase. However, in the case of three-phase networks that are more susceptible to imbalanced problems, an extra signal processing step will be necessary to precisely provide the requisite reference current I^{ref}_{Sabc} under such unfavourable power system conditions.

Table 1. System working parameters

Parameters	***Values***
Source Voltage (ph to ph)	400 V, 50 Hz
Dc-link capacitors	4700 µF & 4700 µF
Controller	P=0.08; I=0.2
Coupling inductor	R=0.9 Ω;1 mH
Nonlinear Load 1:	R= 70 Ω; L= 1.5 H
Nonlinear Load 2:	R=60 Ω; L= 1.3 H
Nonlinear Load 3:	R=55 Ω; L= 1.1 H
Switching frequency	1000 Hz
Dc-link voltage	1000 V

5 Results

The proposed wind energy based three-phase four wire system is developed in the MATLAB / Simulink environment with two different cases. In case – 1 a dq theory based regulator system is considered with the modular FED section. The simulated results are presented from figures 8, 9, 10, 11 & 12, capacitor charging and discharging of currents, dq -axes currents, DC- link capacitor voltage, three-phase Non-linear load currents, active power filter currents, Source currents, source voltages and neutral currents of load and source respectively.

Case – I Simulation with dq-theory:

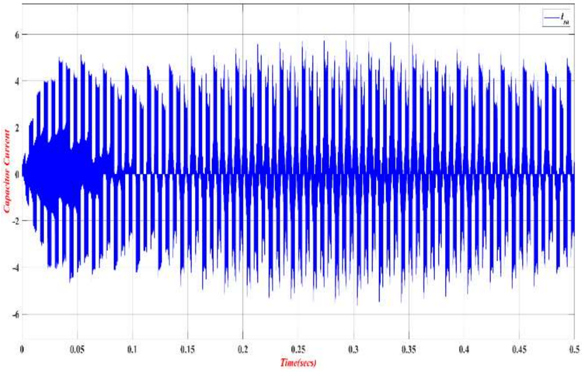

Fig. 8 Capacitor current charging and discharging modes

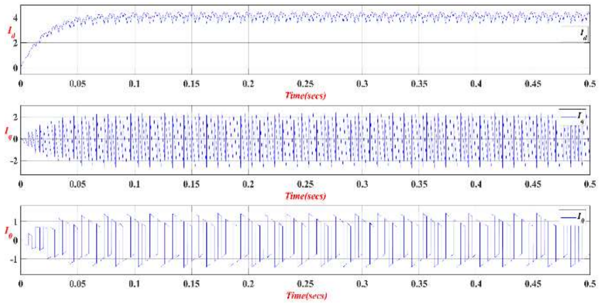

Fig. 9 Simulated currents of dq-coordinates

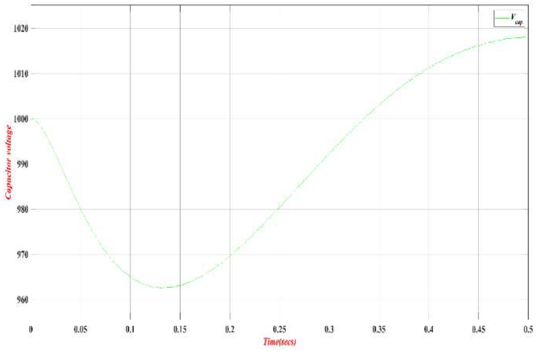

Fig. 10 DC-link Capacitor voltage: Simulated waveform

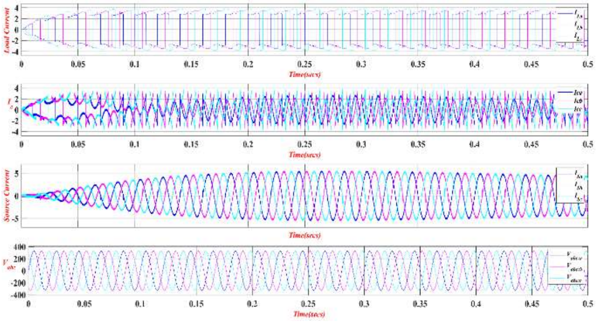

Fig.11. Three-phase simulated waveforms of the projected arrangement. a) Non-linear load currents, b) active power filter currents, c) Source currents and d) source voltages.

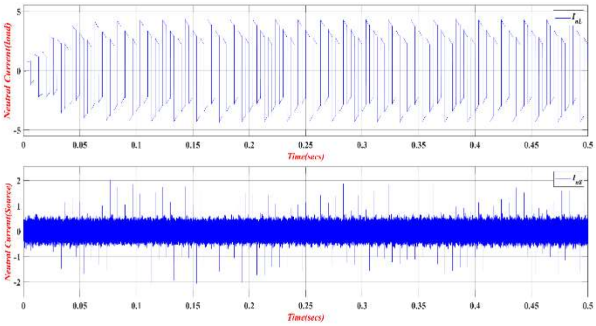

Fig.12. Simulated neutral currents of Load and Source.

Case – II Simulation with pq-theory:

Similarly, in case – 2 a dq theory based regulator system is considered with the modular FED section. The simulated results are presented from figures 13, 14, 15, 16 & 17, capacitor charging and discharging of currents, neutral currents of load and source, DC- link capacitor voltage, pq -axes currents, three-phase Non-linear load currents, active power filter currents, Source currents, and source voltages respectively.

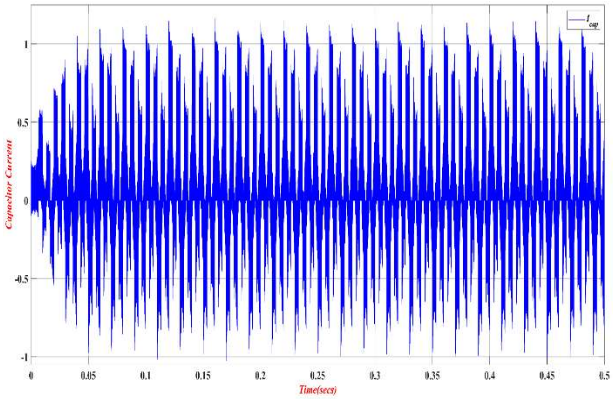

Fig. 13. Capacitor current charging and discharging modes

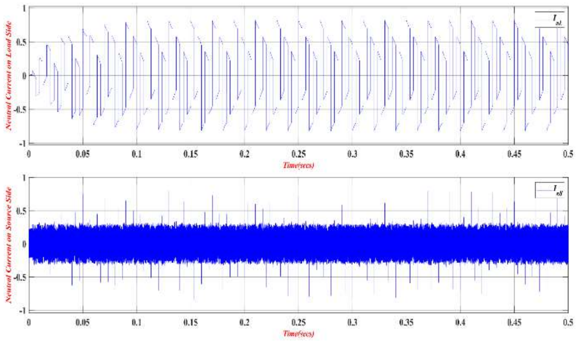

Fig. 14. Simulated neutral currents of Load and Source

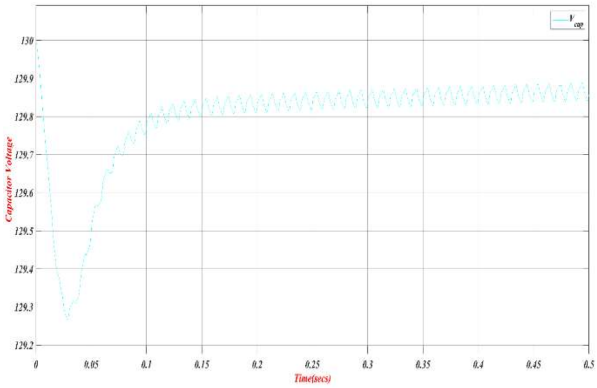

Fig.15. DC-link Capacitor voltage: Simulated waveform

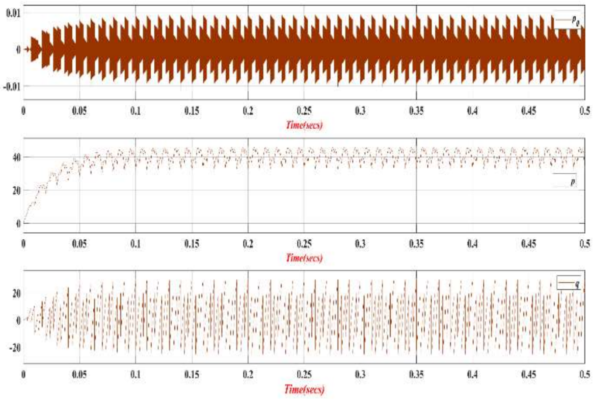

Fig.16. Simulated currents of pq-coordinates

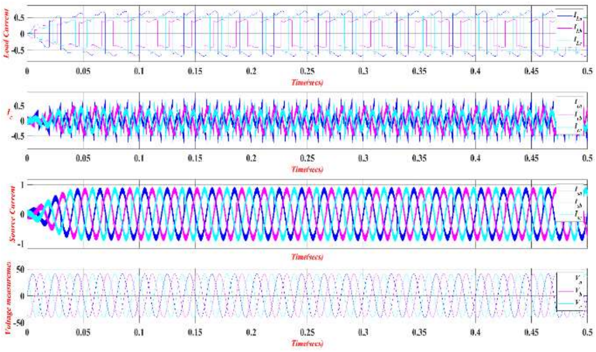

Fig.17. Three-phase simulated waveforms of the projected arrangement. a) Non-linear load currents, b) active power filter currents, c) Source currents and d) source voltages.

6 Conclusion

In summary, this paper projects a novel regulator method for a grid-tied wind system with a three-phase four-wire configuration, aimed at effectively managing various loading conditions. By employing the synchronous reference frame (SRF) method, the proposed system generates a reference current signal that facilitates the operation of a three-phase four-wire parallel connected active power filter (SAPF). The SRF method, known for its control simplicity, is adapted to address the unique challenges of a four-wire network. The newly proposed topology demonstrates its efficacy in minimizing harmonic currents under non-linear, step change, and unbalanced load conditions. The design and performance of the system were validated through simulations using MATLAB/Simulink, confirming its potential for improving power quality in wind energy applications.

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