Shunt Active Line Conditioner Using Notch Adaptive Filter for Unbalanced and/or Distorted PCC Voltage

[1]Muralikrishnan Gopalakrishnan,[2]Santhosh Parani raja manoharan, [3]Ponkumar Ganeshapandiyan
[1,2,3]Department of Electrical and Electronics Engineering, Panimalar Engineering College, Chennai, India

***Abstract*— In this paper, non – ideal Point of Common Coupling (PCC) voltages dealing with 3-phase 3-wire Shunt Active Line Conditioner (SALC) will be presented. The Notch Adaptive Filter (NAF) is developed to control those unbalanced and/or distorted PCC voltage in the distribution system. For the design of SALC, instantaneous power theory is employed which shows best performances evidenced in terms of compensating unbalanced/distorted current of loads even without an ideal voltage circumstance from the simulation results of Matlab / Simpower Sytem tool.**

Keywords- Notch Adaptive filter, Instantaneous power theory, Total Harmonic distortion, dq-filter.

I. INTRODUCTION

Because of the proliferation of the nonlinear loads, there has a significant increase of line losses, instability, and voltage distortion. Industrial applications also have witnessed a constant growth of power electronics converters. Many such converters draw non-sinusoidal current and inject harmonics into the power distribution system. These drawbacks lead to low power factor, higher losses in the transmission and distribution lines, heating of core of transformers and electrical machines, and voltage sags [1].

Various methods have been proposed to mitigate it. Conventionally, passive filters have been broadly used to eliminate load harmonics, due to their low cost, simple structure and high efficiency. However passive filters have the demerits of fixed compensation, large size, undesirable resonances, strong dependence on source impedance, and the variation of filter characteristics with time. Among the different technical alternatives available to improve power quality, active power conditioners have been proposed to compensate the aforementioned problems of passive filters. Various active power conditioner topologies have been presented in the technical literature. The shunt active line conditioner (SALC) is most widely used to eliminate current harmonics, and reactive power compensation [4]. Moreover, it is recognized as a viable solution due to its excellent performance characteristics and simplicity in the implementation. This kind of active filter injects equal compensating currents, opposite in phase, to cancel harmonics or reactive components of the nonlinear load current at the connecting point. The performance and efficiency of SALC depend strongly on control technique of voltage source inverter. Hysteresis current controller and ramp comparison current controller are salient ones. The former is easier to realize with higher accuracy and fast response. However, its switching frequency might fluctuate greatly. The latter can realize constant switching frequency but with relatively lower accuracy and response speed. The abovementioned control techniques are based on traditional PI control [3].

In order to improve the performance of three-phase shunt active power conditioner, various nonlinear control strategies under both balanced and unbalanced loading conditions have been reported in the literature. However, under distorted and/or unbalanced voltage, the instantaneous power theory does not show good performance. In another direction, used the dq-coordinate and LPF to implement compensation which requires reference frame transformation and leads to a more complicated design of the controller. a neural network-based solution was proposed for the control of the SALC operating under the non-ideal voltage conditions. Some other approaches applied Self-tuning filter (STF) to solve the control problem of the SALC in the non-ideal voltage conditions and showed significant performance which are referred as the STF-based pq theory (STF-pq) and the STF-based dq method (STF-dq), respectively [2]. The STF-based methods need to use the PLL for implementation. As a result, a powerful signal processing tool to solve the PCC non-ideal voltages is demanded. In this study, Notch Adaptive Filter (NAF) with its excellent performance is used to extract positive-sequence component (Ps-component) from non-ideal voltages thanks to its fast reaction in comparison to other types of signal processing units. For about 30 years, the adaptive filter method has been developed and, under the environment of the statistical characteristics, its filtering performance is far more than the general fixed parameters filter.

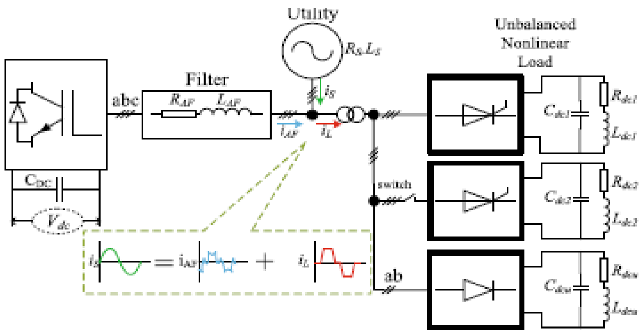


Figure 1. Fundamental principle of shunt active line conditioner

The concept of NAF looks very much similar to that of a Phase-Locked Loop (PLL). However, the PLL is fundamentally different from the NAF in the way that it actively generates its output signal while the NAF (which is frequency based) extracts passively the required output from the input signal. The NAF offers a high degree of insensitivity to power system disturbances, harmonics and other types of pollution existing in the grid signal and structural simplicity because it requires no voltage-controlled oscillator as the PLL does. The NAF is a basic adaptive structure that can be used to extract the desired sinusoidal component of a given periodic signal by tracking its frequency variations. Advanced signal processing methods in both time- and frequency-domains have been developed in the past [7]. Frequency-domain approaches are Fast Fourier Transform (FFT) and Discrete Fourier Transform (DFT) techniques. Important time-domain schemes are the instantaneous dq, the synchronous dq, notch filters, approximated band-pass resonant filters and the stationary frame filters. The initial application of NAF in compensate harmonic components of nonlinear loads was discussed in some researches. A powerful ALC should contain an advanced signal processing performance that can additionally extract sequence-components for compensation purpose. This paper extended our research and gradually shows the following key points:

– The NAF can facilitate duties of ALC under non-ideal voltages with a low investment.

– Symmetrical component transformation is not required in the control of SALC to carry out the proposed solution easier.

– The proposed controller integrated NAF for SALC is feasible for various tested cases.

– That controller has a explicit algorithm, which allows compensating harmonics, reactive power and imbalance currents under unbalanced nonlinear load and non-ideal voltages at PCC.

– Current extraction eliminates the requirement of any high- pass or low-pass filtering as otherwise required by the dq-filter method, $p-q$ and $p-q-r$ theories and so on. The algorithm can also be successfully applied under variable load conditions.

It is noted that during SALC working, currents from the utility are called as compensated currents and currents from SALC as compensating currents or eliminated currents. The target of controller is a sinusoidal utility current controlling strategy instead of the constant utility instantaneous power one. With non-ideal PCC voltage, it is impossible to adopt both strategies at the same time [5].The main contributions of this paper are twofold:

– NAF is applied to control a 3-phase 3-wire ALC in *abc*-coordinate. The algorithm does not necessitate preprocessing, such as high-pass and low-pass filtering, in order to separate the fundamental and the harmonic components.

– Performance of the system is evaluated under the distorted and/or the unbalanced utility voltages and with the unbalanced, the non-linear and the variable load groups respectively.

The proposed controller integrated NAF for SALC is feasible for various test cases. That controller has a simple algorithm, which allows compensating harmonics, reactive power and imbalance currents under unbalanced nonlinear load and non-ideal voltage at PCC.

II. Proposed Controller

The input signals of the controller include utility voltage (vabc), load current (iabcL), converter output current (iabcAF), and dc voltage Vdc, Vdc ref. Since the target is laid on the load, its consuming power is continuously measured and analyzed. Notch Adaptive Filter (NAF) is applied to obtain fundamental Ps- component from the non-ideal voltage instantaneously and accurately. Therefore, the controller can exactly determine the fundamental reactive power of the load and then produce fundamental Ps-sequence ac current orthogonal to the fundamental Ps-sequence ac voltage to provide only that fundamental reactive power. Furthermore, symmetrical component transformation is not required in the control of the active filter making the proposed solution easier to implement in practice [2], [6].

A. *Controller based on instantaneous power theory and signal processing unit (N)*

Under non-ideal PCC voltage conditions, the sum of components ($v^2\alpha + v^2\beta$) will not be constant and alternating values of the instantaneous real and imaginary power have current harmonics and voltage harmonics. Consequently, the ALC does not generate compensation current equal to current harmonics and gives out more load harmonics than that required. To overcome these limitations, a tool using the NAF is introduced to filter out PCC voltages, and then the instantaneous reactive and active powers are calculated. Compared to the previous method reported, the proposed method extracts more complete Ps-component. The input non-ideal voltage is processed by NAF. The dynamic behavior of the newly modified NAF is characterized by set of differential equations. A trade-off between the (steady state) accuracy and (transient) convergence speed can be carried out by adjusting those design parameters. The NAF structure has three integrators. The initial condition for the one that outputs the frequency, ω, is set to the nominal power system frequency, of 2π.60 rad/s as in this study. The initial conditions for all other integrators are set to zero. For a single sinusoid input signal, u(t) = A sin (ωt + φ) where A is magnitude and φ is phase angle, this NAF space has a unique periodic orbit. In the 3-phase system, a synchronization algorithm can be implemented in abc frame and by means of three single phase NAF systems introduced previously. Each single phase NAF is a third-order dynamic system, hence the 3-phase system has a dynamic of nine orders [4]. However, the 3-phase signals have a common frequency, ω, and, therefore, there is no need to estimate the frequency of each phase independently.

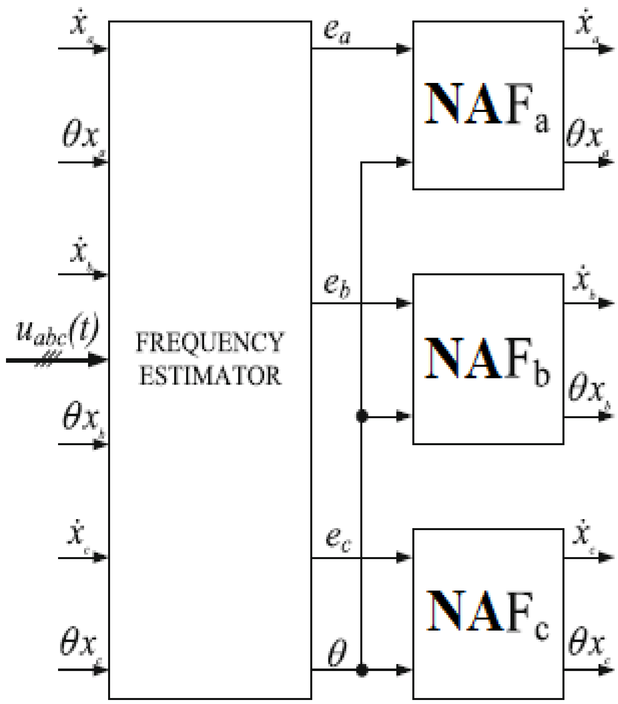


Figure 2. implementation of 3 phase NAF

Moreover, separate operation of NAFs makes the overall system complex for hardware implementation and demands high volume of calculations for software implementation. Additional order might also cause delays and reduce the speed of convergence. A 3-phase NAF for 3- phase systems using a seven-order dynamical NAF system. The fast and accurate detection of the Ps-components of NAF is necessary under non-ideal PCC voltage. The input signals of NAF, $u(t)$ can be decomposed to positive-, negative- and zero-sequence components $u(t) = u_+(t) + u_-(t) + u_0(t)$ and are related to the input signal $u(t)$. The 3-phase NAF introduced previously receives the 3-phase signals $u_a(t)$, $u_b(t)$ and $u_c(t)$. Each sub-filter provides the fundamental component of each phase, its 90-degree phase-shift and its frequency. Then, all the information can be used to calculate the symmetrical components [5]. After extracting fundamental component of voltage, the instantaneous power theory is applied to compensate harmonic loads. Using the Clarke transformation, the instantaneous real power (p_L) and imaginary power (q_L) of load can be calculated.

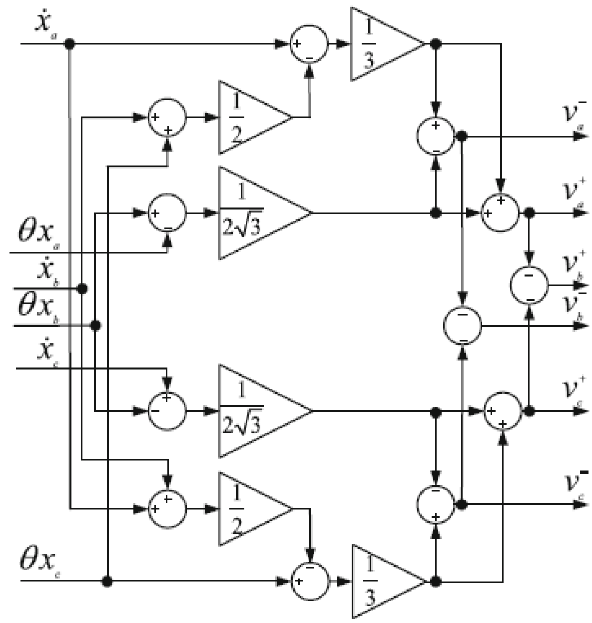


Figure 3. Linear transformation of symmetrical-component calculator

In general, the real and imaginary power include two parts which are average (superscript ¯) one and oscillating (superscript ˜) one realized through a low-pass filter (LPF) (or rarely a high-pass filter). The LPF cutoff frequency must be selected carefully according to the inherent dynamics of loads in order to compensate errors during transients. Unfortunately, the unavoidable time delay of LPF may degrade the controller performance. In practice, a fifth-order Butterworth LPF with a cutoff frequency between 20 and 100 Hz has been used successfully depending on the spectral components in oscillating part that is to be compensated. The average part derives from fundamental component of load current while the oscillating part is resulted from harmonics and negative-sequence (Ns-) components

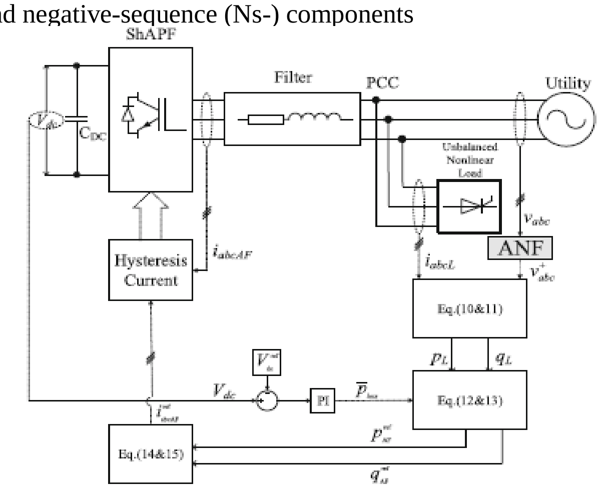


Figure 4. Controller mechanism of SALC converter

After successful compensation, the imaginary power and the oscillating part of real power will come from the SALC. The utility in that case supplies only the average power required from the load. The rest is supposed to be from SALC. Additionally, the *dc* voltage regulator determines an extra amount of real power ($\bar{p}_{loss}$) that causes additional flow of energy to (from) *dc* capacitor C_{dc} to keep its voltage around a fixed reference value. That real power is fed by utility [4]. Furthermore, the *dc* voltage regulation passes through a *PI* controller after via LPF which filters out the switching harmonics existing in the DC capacitor voltage. Using the reverse Clarke transformation, the reference current values in three phases are generated. Finally, the commutation technique is the hysteresis current.

III. SIMULATION RESULTS

The system in Fig. 1 is built using the its controller design shown in Fig. 4 which consists of programmable utility, the unbalanced nonlinear load combining a 3-phase thyristor rectifier and 1-phase diode rectifier, and the SALC module. A 1-phase diode rectifier load is added between phase A and phase B to make unbalanced loads. The DC side load configuration includes *RLC*. Another 3-phase thyristor rectifier is switched during simulated time to evaluate the dynamic performance of the proposed SALC. Some issues should be considered during making simulation:

– The output filter of SAC is supposed to be an inductor L_{AF} for an easier implementation. With *RLC* filter, the transient time lasts longer which makes it difficult to calculate THD values during a time set for the comparison purpose. That L_{AF} is optimally chosen to filter out the switching harmonic from superconductor devices but to be small enough to have fast response.

– The switching load is set up at the AC side. It is impossible

to make a switching active at the DC side with power electronic devices since the complicity of firing currents. Increasing/decreasing the firing angle takes no effect.

– An inductor or an isolated transformer is necessary to put in front of loads. It softens the impacted of power electronic devices of the load which removes the notch in utility currents.

The main parameters of the system used in simulation study are indicated in Table 1. The simulation runs in 18 cycles (0.30 s). The important time instants are as following: at 0.05 s, turn on SALC with conventional instantaneous power theory controller; at 0.10 s, doubled loads; at 0.15 s, non-ideal PCC voltage happens for the basic loads; at 0.20 s, the proposed controller is applied; at 0.25 s, load is double again to test the effect of that controller.

A. Basic NAF-SALC combination

1) Unbalanced PCC voltage:

In this case, Ns-voltage is imposed at 0.15 s and its magnitude is 0.2 p.u. The simulation result is shown in Fig. 5. Since the THD level changes according to the number of measured cycle, it is obtained consistently during a 0.05-s time set for an easy comparison. Without loss of generality, the THD of only phase *a* is measured for that comparison. With the conventional controller, utility current becomes distorted under unbalanced PCC voltage.

TABLE I. SYSTEM PARAMETERS IN SIMULATION

UTILITY	RANGE
Voltage (v_{abc})	200 V
Frequency (f)	60 Hz
R_S , L_S	ideal
SALC	
Dc-link voltage (v_{dc})	500 V
Dc capacitor (C_{DC})	1200 µF
SALC (R_{AC},L_{AC})	(0,1 mH)
Unbalanced Non linear Load Isolated transformer	
Nominal Power	25 KVA
(R_{pri}.L_{pri})	(0.002 pu.0.008 p.u)
(R_{sec},L_{sec})	(0.002 pu.0.008 p.u)
(R_m,L_m)	(500 p.u.500 p.u)
3 phase thyristor rectifier	
($R_{dc\,1}$,$L_{dc\,1}$,C_{dc1})	(1 Ω,1 mH,1 µF)
($R_{dc\,2}$,$L_{dc\,2}$,C_{dc2})	(1 Ω,1 mH,1 µF)
Firing angle	30 ^{0}
I-phase diode rectifier	
(R_{dcu},L_{dcu},C_{dcu})	(1Ω, 1mH, 1 µF)
NAF	
(ξ , Y)	(0.6, 18.000)

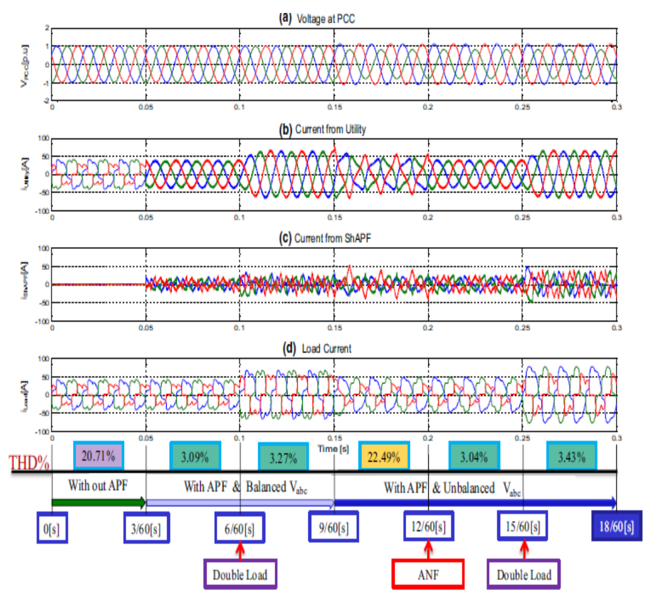


Figure 5. The controller of SALC results under unbalanced voltage

However, during applying the proposed controller, it recovers to the sinusoidal shape. During balanced voltage condition, the ALC works well to compensate THD from 20.71 to 3.09 % at light loads and to 3.27 % at heavy loads. However, during time period from 9/60s to 12/60s when voltage becomes unbalanced, the ALC cannot compensate nonlinear loads where the THD value is at 22.49 %. Applying NAF to the controller, THD value reduces significantly to 3.04 % at light loads and to 3.43 % at heavy loads.

2) Distorted PCC voltage:

In this case, 5th harmonic is also imposed at 0.15 s and its magnitude is 0.5 p.u. The simulation result is shown in Fig. 6. When the PCC voltage becomes non-ideal, the load current subsequently is influenced. Under distorted voltage, a difficult situation using the proposed controller could be observed. Even though NAF extracts well the Ps-voltage, the utility current still faces a high THD value. As the previous case, the conventional controller fails to filter out the harmonic part. It even makes the harmonic from utility current larger at 56.03 %. Applying NAF to the controller, that THD reduces to 7.51 % at light loads and to 9.21 % at heavy loads [8].

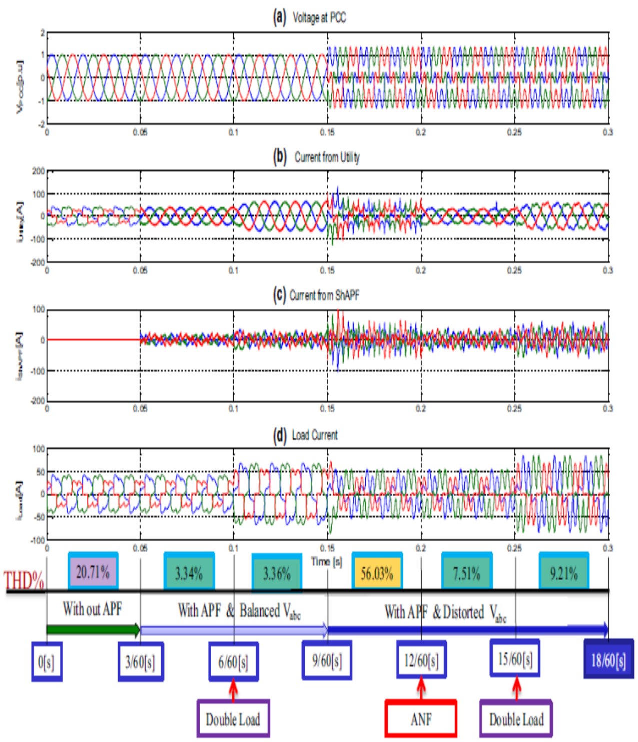


Figure 6. The controller of SALC results under distorted voltage

3) Unbalanced and distorted PCC Voltage:

In this general severe case, both 0.2 p.u Ns-voltage and 0.5 p.u 5th harmonic voltage are imposed at 0.15s. The simulation result is shown in Fig. 7. The NAF still handles well with this case where THD reduces to 8.98% at light loads and to 9.99 % at heavy loads. Furthermore, in all three cases, the proposed controller succeeds in regulating compensated currents from SALC when loads double at 0.25 s. This ability is similar to conventional controller under ideal PPC voltage as seen at 0.10 s. Besides, under some standards, the THD of any current or voltage should be lower than 5%. From the above simulation, the 5th-order harmonic voltage is chosen at 0.5 p.u, which is a relatively high value. And this value will impact on the apparent performance of the proposed SALC. If a lower 0.3 p.u 5th is imposed at PCC voltages, the effectiveness of proposed SAC is more clear as seen in Table 2 by THD index values. However, in distorted case, after doubling load, the THD value is higher than 5%. It requires further step to improve the NAF solution. The following section will soon solve that problem.

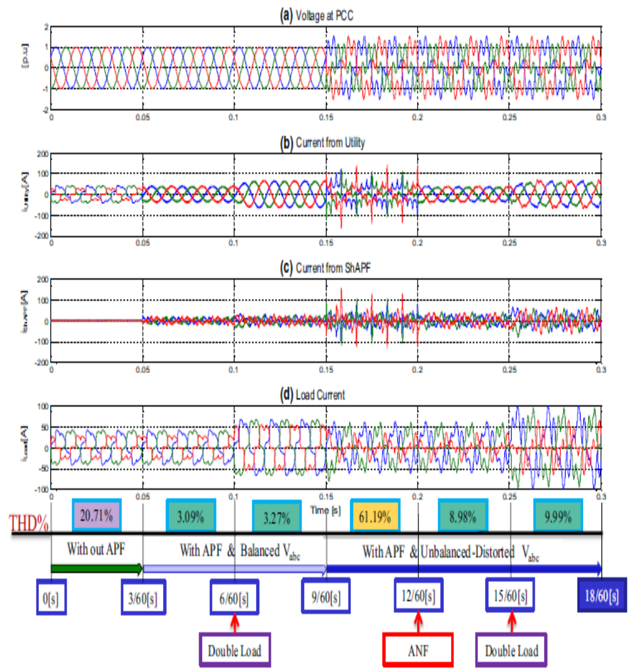


Figure 7. The controller of SALC results under unbalanced and distorted voltage

TABLE II. THD INDEX IN THE CASE OF 0.3 P.U 5TH

Time (s)	0.15 -0.20	0.20-0.25	0.25-0.3
Distorted case: THD (%)	31.25 %	4.50%	5.06%
Unbalanced and distorted case: THD (%)	41.53 %	4.77 %	4.99 %

B. Improved NAF-SALC combination

1) Comparison to dq-filter solution

The mechanism as in Fig. 8 is to convert the from v_{abc} in abc-coordinate to v_{dq} in dq-coordinate and then using LPF to obtain average values of d-voltage (v_d) and q-voltage (v_q). Those average values represent the fundamental Ps-component. After that, the $V\alpha\beta$ are processed by the instantaneous power theory controller. Table 3 referring Table 2 shows the comparison results regarding the THD index while applying both dq-filter controller and the proposed controller in the case of 0.3 p.u 5th harmonic. It is clear that only in the distorted voltage, the performance of the proposed SALC is worse. The NAF-based SALC definitely performs better whenever there are unbalanced components in the PCC voltage.

TABLE III. THD INDEX WHILE USING DQ FILTER

Time (s)	0.20-0.25	0.25-0.3)
Unbalanced case: THD (%)	5.43%	4.73%
Distorted case: THD (%)	3.67 %	4.29
Unbalanced and Distorted case: THD (%)	6.74%	5.40%

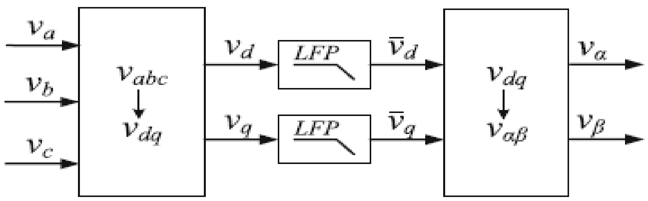


Figure 8. Voltage harmonic filtering diagram of dq filter solution [18]

2) Improved NAF

In this section, it will be shown how the improved NAF can extract more precisely the fundamental Ps-component when PCC voltage contains harmonic components. As a result, the sub-filter in Fig. 2 is modified and replaced by the others shown in Fig. 9.

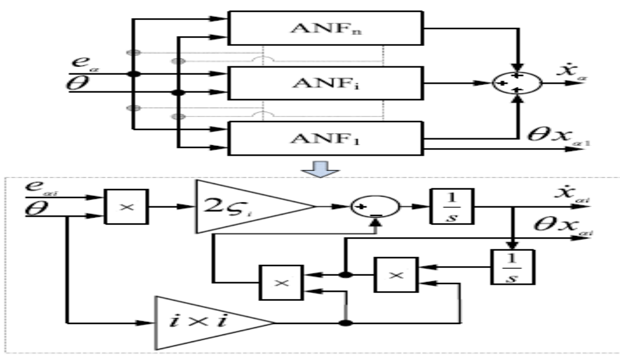
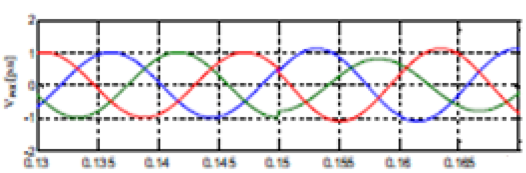
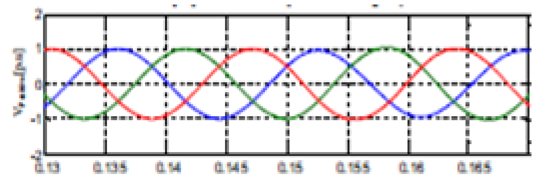


Figure 9. Structure of sub-filters of improved ANF

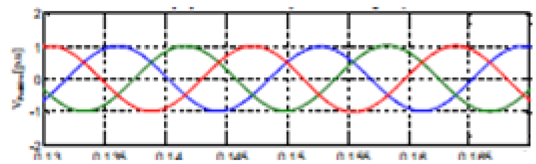
The Fig. 10 synthesizes their extraction waveforms, where the pure Ps-voltage extraction is an objective. The observed duration is shortened in [0.13–0.17s] during the instant of the non-ideal voltage injection for a better view. The readers could take a closer look to distinguish visual differences of extracted waveforms. Unbalanced at Fig. 10. a, the NAF successfully extracts the Ps-component. However, the improved NAF works better. Because of its better performance dealing with unbalanced voltage



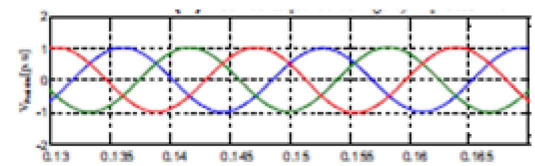
(i) Unbalanced voltage at pcc



(ii) Positive sequence voltage by LPF



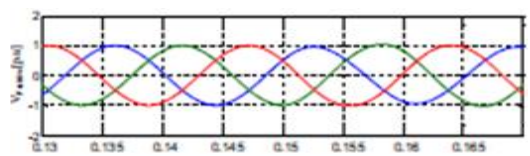
(iii) Positive sequence voltage by NAF



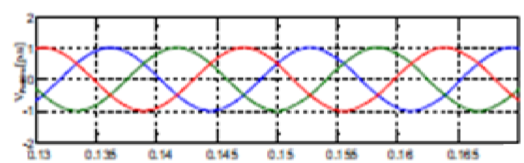
(iv) Positive sequence voltage by improved NAF

Fig 10. a. Under Unbalanced Voltage

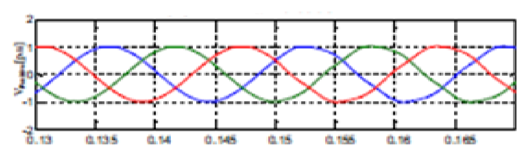
Meanwhile, dq-filter extracts an impure balanced voltage. Distorted at Fig. 10b, the dq-filter even makes extracted voltage unbalanced. The NAF brings a slightly distorted Ps-voltage. Successfully, the improved NAF successfully extracts the almost pure Ps-component of PCC voltage.



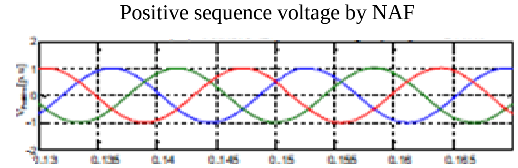
Distorted Voltage at pcc



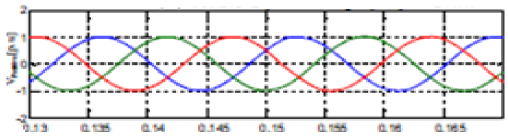
Positive sequence Voltage by LPF



Positive sequence voltage by NAF



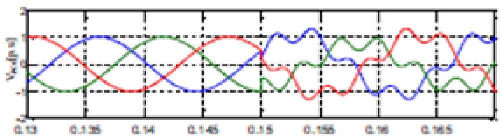
Positive sequence voltage by NAF



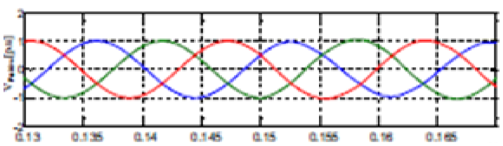
Positive sequence voltage by improved NAF

Fig 10. b. Under Distorted Voltage

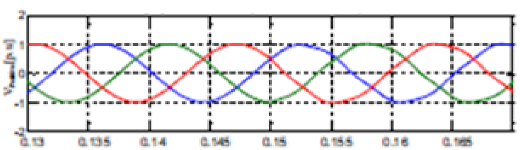
Unbalanced and distorted At Fig. 10c, the improved NAF under this tough circumstance extracts well the Ps component from v_{PCC} as two previous cases. It should be noted that, the NAF brings a worse Ps-component waveform compared to dq-filter. However, the THD value of utility currents in that case still smaller.



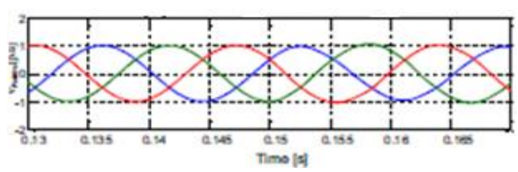
Unbalanced and Distorted Voltage at pcc



Positive sequence Voltage by LPF



Positive sequence voltage by NAF



Positive sequence voltage by improved NAF

Fig. 10. c. Under Unbalanced and Distorted Voltage

Figure 10. PS component extraction capability

The eventual influences of extracted waveforms in Fig. 10 are pointed out in Table 4. The THD indexes shown while using the improved NAF validates the novel design of proposed SLAC. As expected, while the PCC voltage is only unbalanced, the THD values are similar to those of the previous NAF.

TABLE IV. THD INDEX WHILE USING IMPROVED NAF

Time (s)	0.20-0.25	0.25-0.30
Unbalanced case: THD (%)	3.04%	3.43%
Distorted case: THD (%)	3.21%	4.31%
Unbalanced and Distorted case: THD (%)	3.52%	4.23%

However, whenever there is a harmonic component in PCC voltage, the SALC using the improved NAF obtains significantly smaller THD values and better than using dq filter. It is reminded that the THD values, 4.31 % using the improved NAF, is still higher than that of 4.29 % using dq-filter during doubling loads although this difference is not too significant.

Since the THD calculation for a 3-cycle includes waveform during the transient response, the complex NAF would perform worse. For steady-state condition, the improved NAF extracts Ps-component better than dq filter. For example, if the THD value is calculated for a 5-cycle, the value of 3.04 % using the improved NAF and 3.11%using dq-filter are obtained. Eventually, the improved NAF shows itself as a better solution for all of the cases.

IV. CONCLUSION

In this paper, a SALC controller is proposed under non-ideal PCC voltage using NAF. The numerical SimPower Systems simulation has validated the effectiveness of that controller compared with conventional dq-filter methods. Especially, integrating an improved NAF to the controller is very promising as an alternative to dq-filter application in distribution system where the unbalanced nonlinear voltage is predominant.

REFERENCES

[1] T.K.Y Komatsu, “A control method for the active power conditioner in unsymmetrical voltage systems,” Int J Electron, Vol. 86, No. 10, pp.1249, June 1999.

[2] Y.LB.R. Lin, “Three-phase power quality compensator under the unbalanced sources and nonlinear loads,” IEEE Trans Ind Electron, Vol.51, No.5, pp.1009, March 2004.

[3] C.Y.G.W. Chang, “Optimisation-based strategy for shunt active power conditioner control under non-ideal supply voltages”. IEE Proc Electr Power App, Vol.152, No.2, pp.182, April 2005.

[4] B.B.J.J.C.H. Kim, F. Blaabjerg, “Instantaneous power compensation in three-phase systems by using p-q-r theory,” IEEE Proc Electr Power Appl, Vol. 17, No.5, pp.701, Sep. 2002.

[5] E.O. Murat Kale,” Harmonic and reactive power compensation with shunt active power conditioner under non-ideal mains voltage.” Elect. Power System Res., Vol. 74, No.3, pp. 363, Oct. 2005.

[6] E.O. Mehmet, U. car, “Control of a 3-phase 4-leg active power conditioner under non-ideal mains voltage condition,” Elect Power System Res., Vol. 78, No. 1, pp.:58, Sep. 2008.

[7] S.M.R.T. Rafiei, R. Ghazi, “Ieee-519-based real-time and optimal control of active filters under nonsinusoidal line voltages using neural networks,” IEEE Trans Power Del., Vol. 17, No.3, pp.815, Aug. 2002.

[8] N.K. Nguyen, A. Wira, D. Flieller, “Neural networks for phase and symmetrical components estimation in power systems,” In: 35th Annual Conference of IEEE Ind. Electron., IECON 09, pp 3252, April 2009.