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Enhancement of Power Quality with Sliding Mode Controlled Hybrid Active Power Filter Based on Variable Scaling Hybrid Differential Evolution

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***Abstract*— Power quality is one of the major concerns now-a-days.the major concentrations in power quality disturbances are kept harmonic current at source side due to inception of non linear loads. Hybrid active filter is one of the most versatile devices to mitigate these power quality disturbances. Hybrid power filter consists of shunt active filter in series with passive filter. The reference currents are generated with sliding mode controller. The gating pulses for the switches in voltage source inverter of active filter are generated by hysteresis band current controller. The PI controller in sliding mode controller is further optimized with variable scaling hybrid differential evolution technique. The effective simulations are carried out in MATLAB/Simulink.**

Index terms: Power Quality (PQ), Hybrid Active Power Filter (HAPF), Indirect Current Controller (ICC), Hysteresis Band Current Controller (HBCC), Total Harmonic Distortion (THD), Variable Scaling Hybrid Differential Evolution (VSDHE).

List of symbols

V_{sa}, V_{sb}, V_{sc}	*Source voltages at phase a, b, c*
I_{sa}, I_{sb}, I_{sc}	*Source currents at phase a, b, c*
$I_{sa}^*, I_{sb}^*, I_{sc}^*$	*Reference Source currents at phase a, b, c*
U_{sa}, U_{sb}, U_{sc}	*Unit current vectors for phase a, b, c.*
I_{sx}	*Source current at phase x, where x= a, b, c.*
V_{sx}	*Source voltage at phase x, where x= a, b, c.*
V_e	*tracking error*
V_{sm}^*	*Peak supply voltage.*
I_{sm}	*Peak supply current.*
V_{dc}	*Voltage across dc link capacitor.*
V_{dc}	*Reference dc bus voltage*

I. INTRODUCTION

Now-a-days in power systems, Power electronics devices are used in industries as well as domestic applications also. Such types of devices are converters, uninterrupted power supply, and switching devices. By using these non-linear loads we have so many advantages like economical, energy efficient and flexible. The nature of non-linear loads is injected harmonics into source side harmonic current. If not controlled these harmonics causes so many problems such as poor power factor and less efficiency.

For elimination of these problems by using hybrid active power filter. It depends upon two types of considerations i.e., reference currents and controlling system. The reference currents are generated by per unit voltages from supply voltages. The controller is used to control the DC bus voltage i.e., sliding mode controller. Here two breakers are connected with variable non-linear loads the pi controller does not satisfy the work under load variations. The sliding mode controller is suitable to control the DC bus voltage of hybrid active power filters such conditions. SMC is a advance PID control method and it is only consider variation of performance of the system. The design of hybrid active power filter purpose is to elimination of harmonics for wide range of variation of load current under difference non-linear load. Therefore the sliding mode control scheme yields an improved total harmonic distortion performance compared with hysteresis band current control method. The further optimization technique is suitable for sliding mode controlled hybrid active power filter is variable scaling hybrid differential evolution. It is used to alleviate the total harmonics distortion compared to sliding mode controller.

The variable scaling factor based on the 1/5 success rule is used in the variable scaling hybrid differential evolution method to overcome the disadvantage of the random scaling factor and fixed scaling factor and reduce the problem of the selection of a mutation operation in the hybrid differential evolution..

II. HYBRID ACTIVE POWER FILTER

Hybrid active power filter is basically a combination of active filter and passive filter .HAPF is a various combinations are available. They are

1. Shunt active filter + Series active filter
2. Shunt active filter + Shunt passive filter
3. Shunt active filter + Series passive filter
4. Series active filter + Shunt passive filter

There are the combinations are available to compensate the reactive power and eliminate the harmonic current. In this paper another type of combination is consider i.e., the combination of shunt active filter and shunt passive filter. Each combination of these hybrid filters are different performance, but this type of combination is commonly used.

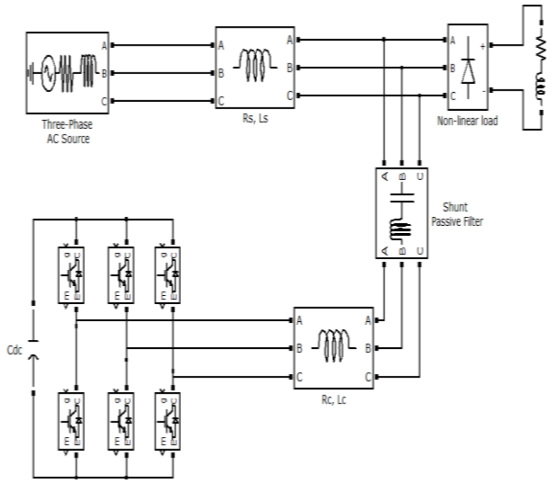


Fig 1: Shunt hybrid active filter

A. *Active Filter*

Active power filter is used to compensate source current harmonics by injecting equal-but opposite harmonic compensating current. The shunt active power filter operates as a source current injecting the harmonic current components generated by non-linear load but phase shifted by 180°. Active filter consists of two components i.e., three phase voltage source inverter and dc link capacitor

B. *Passive Filter*

It is used to compensate the lower order harmonics generated by non linear load, and also improving their power factor. Higher order harmonics are passed to active filter where in controlling dc bus voltage reduces the current harmonic as a result to improve overall power quality of the system. The advantages of passive filter is no perfect tuning is required and active power filter is introduce to the system any time when it is already installed in the system.

III. BLOCK DIAGRAM

The main objective of this project is controlling the hybrid active power filter provide compensating current harmonics signal to the system in such away the waveform of supply current remain sinusoidal and at the same time the harmonics are generated by non-linear load. The reference source current can be applicable for applying the filtering algorithm i.e., indirect method of sensing current. This type of method taking unit current vectors from the source voltages. These units current vector, when multiplied with the reference source current i_{sm}^* provide with the three phase reference sinusoidal currents in phase with the supply voltage. When compared with PQ theory and SRF theory the control approach is low cost and simple. The controlling of dc link voltage is used for low and medium power application. Which is easy to implement and very simple, it is do not need to sense harmonic and var. To calculate the reference currents to consider feedback signal from the dc bus voltage. Three types of controllers are obtainable for controlling dc bus voltage in the literature PI controller, sliding mode controller and variable scaling hybrid differential evolution. In this control strategy the dc bus voltage is sensed and compared with respective dc bus voltage as shown in figure 2.

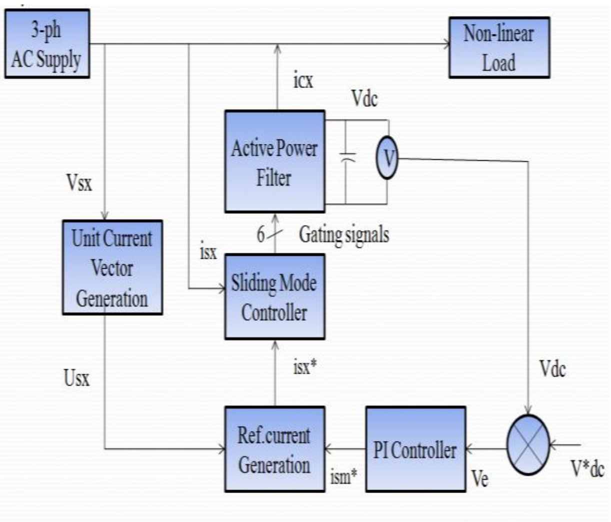


Fig 2: control strategy for hybrid active power filter

The error signal is then conditioned and considered as the reference supply current I*sm. The three phase unit current vectors (usa, usb, usc) are obtained from the supply voltages (vsa, vsb, vsc) and the peak supply voltage (Vm). These unit current vectors, when multiplied with reference supply current (I*sm), result in three phase reference supply currents (i*sa, i*sb, and i*sc). The three phase reference supply currents and sensed supply currents (isa, isb, and isc) are the inputs for the pulse generator, generating the firing pulses as gating signals to the MOSFETs of the active power filter. The PI- controlled hybrid active power filter does not work satisfactorily under load variations; the sliding mode control is preferred to regulate the DC bus voltage of active power filter under such conditions. Here sliding mode control is implemented to achieve the desired result.

IV. REFERENCE CURRENT CALCULATION

Reference currents are generated from the reference currents generator. The schematic block diagram of the reference currents generator is shown as Figure 3. The three-phase unit sinusoidal signals should have the same phase with the supply voltage, so three PLLs are used to get unit sin (sin wt, sin (wt−120), sin (wt+120)). The parameters of PI regulator find the static and dynamic performance of the DC voltage. By proper parameters setting, the DC voltage can be well maintained around the given value but not strictly equal to that value. Accordingly, the output of PI regulator is also stable. There is a locked ratio between the PI regulator's output and load current amplitude, so Ism* can be formed by multiplying output of PI controller and the ratio. Otherwise, a low-pass filter is added after the PI regulator and its output which is much higher stable than PI regulator's are applied as Ism*. Multiplying the unit sinusoidal signals and Ism*, the supply reference currents Isa*, Isb*, and Isc* can be formed.

A. *Unit Current Vector Generation*

The peak amplitude of the supply voltage is derived from sensed three-phase sinusoidal voltage as

$$V_{sm}= [2/3(V_{sa}^2+V_{sb}^2+V_{sc}^2)]^{1/2} \quad (1)$$

Now the three phase unit vectors can be taken as

$$U_{sa}= V_{sa}/V_{sm} \quad (2)$$

$$U_{sb}= V_{sb}/V_{sm} \quad (3)$$

$$U_{sc}= V_{sc}/V_{sm} \quad (4)$$

These unit current vectors, when multiplied with the reference supply current Ism* provide with the three phase reference sinusoidal currents in phase with the supply voltage.

$$I_{sa}^*= I_{sm}^*.U_{sa} \quad (5)$$

$$I_{sb}^*= I_{sm}^*.U_{sb} \quad (6)$$

$$I_{sc}^*= I_{sm}^*.U_{sc} \quad (7)$$

The reference currents when compared with the sensed actual currents in the hysteresis band current controller provide with the switching signals for the active power filter.

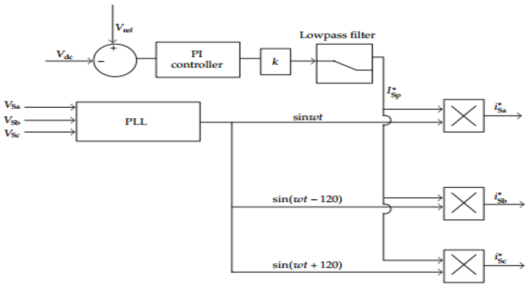


Fig 3: Schematic of the reference currents generation.

B. *Sliding Mode Controller*

Sliding mode control is a non-linear method which can control a system even when there is not accurate mathematical model. Certainly, controlling a system with one degree is simpler than a system with n- degree. Hence, sliding mode control method tries to control an n- degree system by manipulating its one degree representative system. This system in named as sliding surface.

Sliding mode control is deterministic (only bounds of variations are considered), non-linear (the corrective term is non- linear) and robust (once on the sliding surface, the system is robust to bounded parameters variations and bounded disturbances).due to maintaining the system stability and it performance of the presence in the non ideal parameters.

It is applied in the presence of modeling inaccuracies, parameter variations and disturbances, provided that the upper bounds of their absolute values are known. The expected results are confirmed through simulation.

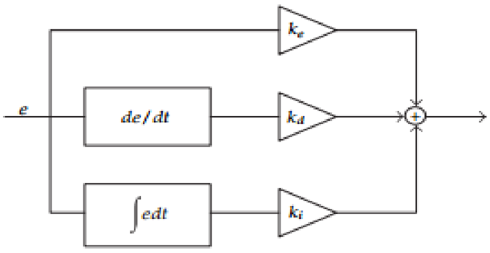


Fig 4: Schematic Of The Sliding Mode Control.

Sliding mode control is a powerful control method that can produce a very robust closed loop system under plant unpredictability and external disturbances, because the sliding mode can be designed entirely independent of these effects. Also, sliding mode controller are inherently stable. However several disadvantages exist foe sliding mode control. An assumption for SMC is that the control can be switched from one value to another infinitely fast.

In practice it is unworkable to change the control of infinitely fast because of the time delay for control computational and physical limitations of switching devices. As a conclusion, chattering occurs in steady state and appears as an oscillation that may excite not a model high frequency dynamics in the system. Hysteresis can be used to regulate the switching frequency, but a constant switching frequency can be guaranteed. However, there is always chattering in the sliding mode when hysteresis is used. As a result, the system is able to approach the sliding mode but not able to stay on it.

This control technique is attractive for the control of non-linear systems because the discontinuous nature of the control action results in outstanding robustness features such as insensitivity to parameter variations and rejection of external disturbances also, the system dynamic involved in a sliding mode control strategy is solely governed by the choice of the switching.

The main idea is to bring and keep the error on a sliding surface such that the system is insensitive to the disturbances and parameter changes. Sliding mode control is used to regulate voltage of capacitor used in inverter. It improves the dynamic response of the system and provides faster convergence. The performance of SMC is compared with conventional PI controller is good solution for the hybrid shunt active power filter. Because of it is suitable for variation of loads and simple to use in large systems.

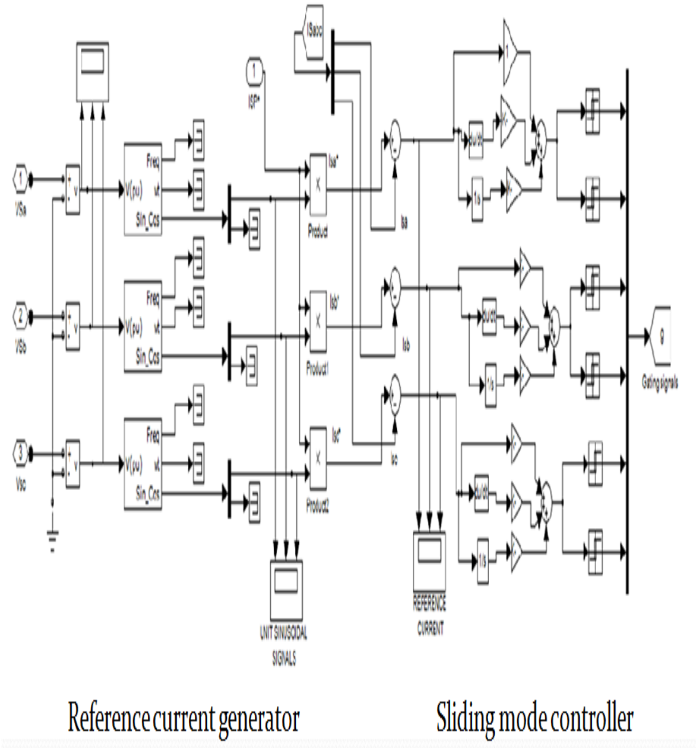


Fig 5: calculation of reference current

C. *Hysteresis Band Current Controller*

A carrier less hysteresis band current controller is used over the reference currents (i*sa, i*sb, and i*sc) and sensed supply currents (isa, isb, isc) to generate the switching signals for the MOSFETs of the current controlled VSI working as an active power filter. The switching signals are obtained as follows If isx > (i*sx+ hb), upper switch of xth leg is ON and lower switch is OFF, and

If isx < (i* sx+ hb), upper switch of xth leg is OFF and lower switch is ON,

Where 'hb' is the hysteresis band current controller around the reference current at each phase and x =a, b, c, which stands for three legs of PWM converter.

In response to the switching signals generated by controller, active power filter shapes the source currents to sinusoidal and it compensates the source side harmonics of the nonlinear load.

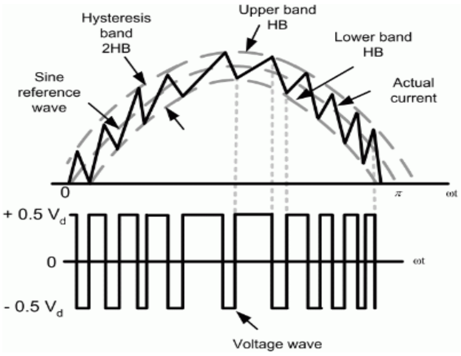


Fig 6: hysteresis band current controller

D. *Selection Of L_c, C_{dc}, V_{DC}*

To keep harmonic distortion in source current within limits, a desirable condition is that the DC bus voltage across the capacitor should rise up to around double the peak source voltage. This choice makes the transient response of the active filter better, as capacitor has sufficient stored energy to meet the requirement of sudden load changes. A constant DC voltage should be maintained across the capacitor with minimum ripples, Steady state as well as transient response must be fast. The DC bus capacitance of the APF system can be calculated from the energy requirement of the capacitor

$$\Delta e_{dc}= 1/2C_{dc} [(V_{dc}^{*})^2-(V_{dc})^2] \qquad (8)$$

Here Δe_{dc} is the energy required by the capacitor to be stored for keeping the DC bus voltage near reference value. Design of filter inductance (Rc, Lc) depends upon the switching frequency of the hysteresis band current controller. The APF circuit shown in Fig.1 can be represented by equation

$$R_cI_c+L_cdi_c/dt+V_c= V_s \qquad (9)$$

Where Vc is the voltage at the VSI-midpoint. Average value of Vc is assumed equal to the addition of voltage vs and voltage drop across ripple filter (L_c, R_c). Voltage drop across inductor of the ripple filter is considered to be around 10% of the supply voltage, drop across resistance Rc is very small compared to that across Lc and therefore can be neglected. Therefore the voltage across ripple filter can be taken as Vc=1.1Vsm.

Thus previous equation becomes

$$L_c.di_c/dt=-V_c+V_s=-1.11V_{sm}+ V_{sm} \qquad (10)$$

Lower value of ripple filter inductance is selected for taking into account the variation in switching frequency. Hysteresis bandwidth of controller is taken as ±0.2. Calculated values of Cdc, Vdc and Lc and nearer values are implemented on the system and system performance judged on parameters %THD (Table-1). The calculated system parameters are- Cdc=2200 µF, Vdc= 880V and Lc=5mH.

V. SIMULATION RESULTS

A simulation model of the studied hybrid active power filter is developed in MATLAB environment. The supply system used in 415V,3-phase, 50 Hz sinusoidal. The nonlinear system considered for compensation is 4kVA diode rectifier with RL-load. Simulation results are obtained for both steady state and transient conditions. Different parameters used for simulation study are listed in Appendix I. Fig.5 shows the simulation waveforms in steady state and Fig.6 (a-c) show %THD of load current and source current for SM-controlled and PI- controlled hybrid active power filters respectively. The source current is observed to be sinusoidal with power factor approaching unity, while the %THD in the source current is well below the IEEE 519 limits in both the cases. It is observed that the DC link voltage settles to a lower value in SM controlled HAPF as compared to PI- controlled HAPF, with lower transients in source current.

The simulation results for active power filter switched on and in change in load for HAPF with both the controllers respectively are given. The active power filter is switched on at 0.1 sec. It is found that the supply current, active power filter current and DC- bus voltage settles to steady state condition in less than 1 cycle after the active power filter is switched on in case of SM controlled HAPF as compared to slow responding PI controlled HAPF, wherein the steady state value is reached after 2 cycles. As the load current increased or decreased, the supply current also changes accordingly and active power filter current changes to meet the requirement. At transient condition i.e. under load changes the SM controlled HAPF again shows faster response with less overshoot/ dip in DC link voltage as compared to PI- controlled HAPF. The sliding mode controlled hybrid active power filter compensates harmonics under steady state as well as during transients.

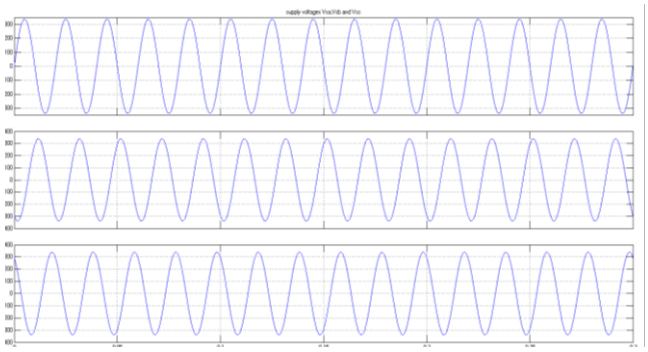


Fig 7: waveform of supply voltages V_{sa}, $V_{sb,}$ and V_{sc} for sliding mode control.

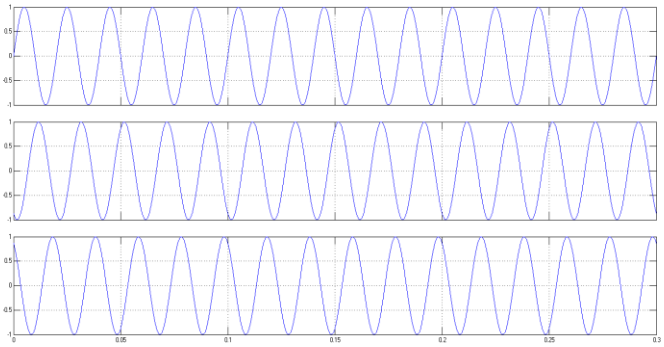


Fig 8: Waveform of unit sinusoidal signals U_{sa}, U_{sb}, and U_{sc} for SMC.

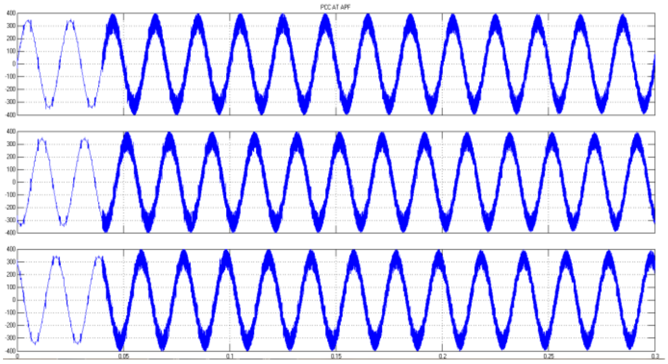


Fig 9: Waveform of voltages on APF connection point.

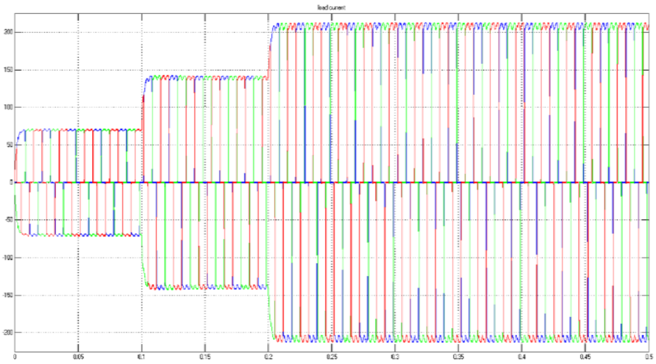


Fig 10: Waveform of load currents $I_{la,}$ $I_{lb,}$ and I_{lc} for SMC.

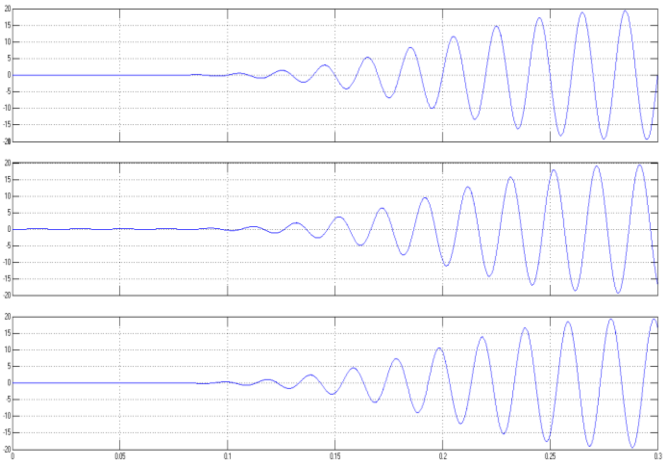


Fig 11: Waveform of three phase reference currents.

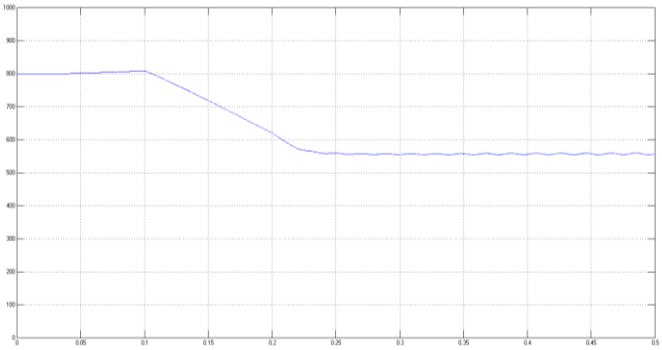


Fig 12: Waveform of DC voltage

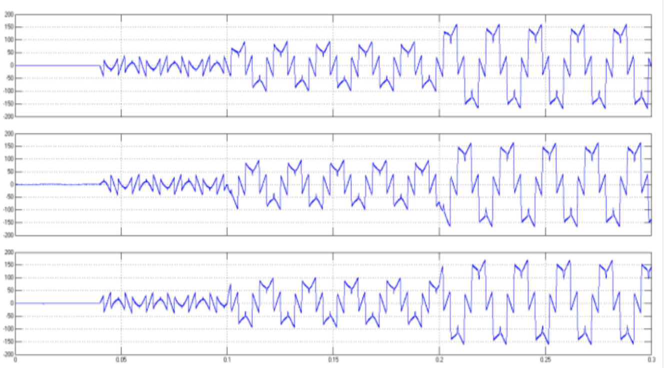


Fig 13: Waveform of compensating currents I_{ca}, I_{cb}, and I_{cc}

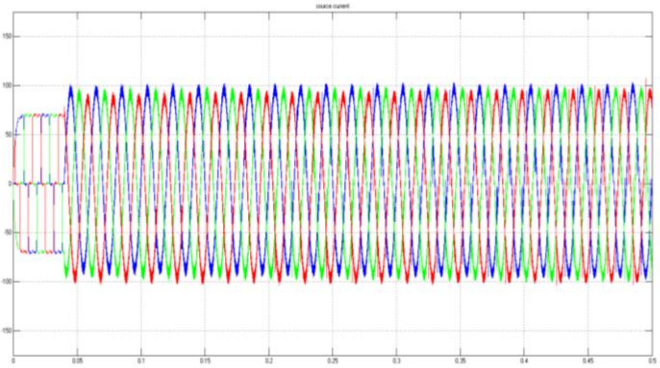
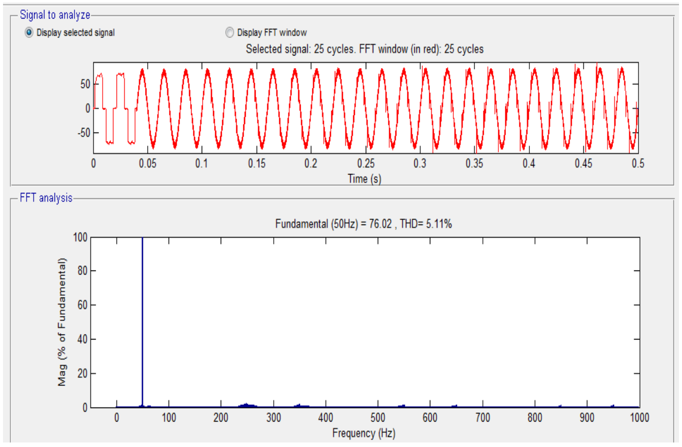


Fig 14: Waveform of source currents I_{sa}, I_{sb}, and I_{sc} for sliding mode control.



Selected signal: 25 cycles. FFT window (in red): 25 cycles

Fundamental (50Hz) = 76.02 , THD= 5.11%

Fig 15: THD of supply current with designed sliding mode controller.

VI. VSHDE ALGORITHM

The major idea of the variable scaling hybrid differential evolution(VSHDE) is to use the variable scaling factor positioned on the1/5 success rule of the evolution strategies to overthrown the disadvantages of the fixed and random scaling factor used in the hybrid differential evolution method. The formula of updating scaling factor based on the 1/5 success rule of evolution strategies is used to adjust the scaling factor. The 1/5 success rule developed as a ending of the process of optimizing convergence rate of two functions (the so-called corridor model and sphere model. The formula of updating scaling factor is as follows:

$$F^{t+1} = \begin{cases} c_d \times F^t, & \text{if } p_S^t < 1/5 \\ c_j \times F^t, & \text{if } p_S^t > 1/5 \\ F^t, & \text{if } p_S^t = 1/5 \end{cases} \qquad (11)$$

Where pt
S is the frequency of outstanding mutations measured. The successful mutation defining the fitness value of the perfect individual in the next generation is better than that the perfect individual in the current generation. The fundamental value of the scaling factor, F, is set to 1.2 . The factors of cd = 0.82 and cj = 1/0.82 are used for balancing, which should be taken place for every q iterations. The iteration index q suggested by is equivalent to 10b, where b is a constant. When the migration operator is operated, the value of scaling factor is defined as follows:

$$F = 1 - \frac{iter}{itermax} \qquad (12)$$

where iter and iter max are the number of current iteration and the ultimate iteration, respectively. And, the scaling factor can be restart as when the scaling factor is too small to find best solution in the solution process. Properly, the variable scaling hybrid differential evolution algorithm is briefly expressed in the following:

- Step1. Initialization

Input system data and develop the population. The initial population is select randomly and would trail to cover the total parameter space uniformly. The uniform probability distribution for all random variables as following is assumed:

$$Z0\,i = Zi,min + \sigma i(Zi,max - Zi,min),\ i = 1, \ldots, Np \qquad (13)$$

where σi ∈ [0,1] is a random number. The initial process can produce Np individuals of Z0 i randomly.

- Step 2. Mutation action five strategies of mutation operation have been introduced. The essential ingredient in the mutation operation is the inequality vector. Each individual pair in a population at the G-th generation defines a difference vector Djk

$$Djk = ZG\,j - ZG\,k \qquad (14)$$

The mutation process at the G-th generation begins by randomly selecting either two or four population individuals ZG j , ZG k , ZG l , and ZG m for any j, k, l and m. These four individuals are then combined to form a difference vector Djklm as

$$Djklm = Djk + Dlm = (ZG\,j - ZG\,k) + (ZG\,l - ZG\,m) \qquad (15)$$

A mutant vector is then proposed based on the present individual in the mutation process by

Zˆ G+1 i = ZG p + F • Djklm, i = 1, ..., Np (16)

Where scaling factor F is a stable (constant). And, j, k, l and m are randomly selected. The perturbed individual in is essentially a noisy replica of ZG p . Herein, the parent individual ZG p depends on the circumstance in which the type of the mutation operations is employed.

- Step 3. Crossover operation In order to develop the diversity of further individuals at the next generation, the perturbed individual of Zˆ G+1 i and the present individual of ZG i are chosen by a binomial distribution to progress the crossover operation to produce the offspring. Each gene of i-th individual is reproduced from the mutant vectors

Zˆ G+1 i = [Zˆ G+1 1i ,Zˆ G+1 2i , ...,Zˆ G+1 ni] (17)

and the present individual

ZG i = [ZG 1i , ZG 2i , ..., ZG ni] (18)

That is Zˆ G+1 gi = ZG gi,

if a random number > Cr Zˆ G+1 gi , otherwise where i = 1,...,Np; g = 1,...,n; and the crossover factor Cr ∈ [0,1] is assigned by the user.

- Step 4. Estimation and selection the parent is replaced by its offspring if the fitness of the offspring is later than that of its parent. Contrarily, the parent is retained in the later generation if the fitness of the offspring is worst than that of its parent. Two forms are represented as follows:

ZG+1 i = argmin{f (ZG i), f (Zˆ G+1 i)} (18) ZG+1 b = argmin{f (ZG i)}

Where Argmin means the argument of the minimum.

- Step 5. Migrating operation if required In order to effectively enhance the investigation of the search space and reduce the choice pressure of a little population, a migration phase is introduced to regenerate a new varied population of individuals. The new population is employed based on the best individual ZG+1 b. The g-th gene of the i-th individual is as follows:,

$$Z_{ig}^{G+1} = \begin{cases} Z_{bg}^{G+1} + \sigma_i\left(Z_{g\min} - Z_{bg}^{G+1}\right), & \text{if } \delta < \dfrac{Z_{bg}^{G+1} - Z_{g\min}}{Z_{g\max} - Z_{g\min}} \\ Z_{bg}^{G+1} + \sigma_i\left(Z_{g\max} - Z_{bg}^{G+1}\right), & \text{otherwise} \end{cases} \quad (19)$$

where σi and δ are randomly generated numbers uniformly distributed in the range of [0,1]; i = 1,...,Np and g = 1,...,n. The migrating operation is executed only if a measure fails to match the desired clearance of population diversity. The measure is defined as follows:

$$\varepsilon = \sum_{\substack{i=1\\ i\neq b}}^{N_p} \sum_{g=1}^{n} \frac{\eta z}{n(N_p-1)} < \varepsilon_1 \quad (20)$$

where

$$\eta z = \begin{cases} 0, & \text{if } \varepsilon_2 < \left| \dfrac{z_{gi}^{G+1} - z_{bi}^{G+1}}{z_{bi}^{G+1}} \right| \\ 1, & \text{otherwise} \end{cases} \quad (21)$$

Parameter ε1, ε2 ∈ [0, 1] expresses the desired tolerance for the population diversity and the gene diversity with respect to the best individual. ηZ is the scale index. It can be seen that the value ε is in the range of [0,1]. If ε is smaller than ε1, then the migrating operation is executed to generate a new population to escape the local point; otherwise, the migrating action is turned off.

- Step 6. Updating the scaling factor if necessary the scaling factor should be updated as in each and every q iterations. When the migrating operation performed or the scaling factor is too small to find the best solution, the scaling factor is reset.
- Step 7. Repeat step 2 to step 6 until the maximum iteration quantity or the selected fitness is accomplished.

The computational process of the variable scaling hybrid differential evolution for solving economic dispatch systems is stated applying a flowchart as shown in fig 16.

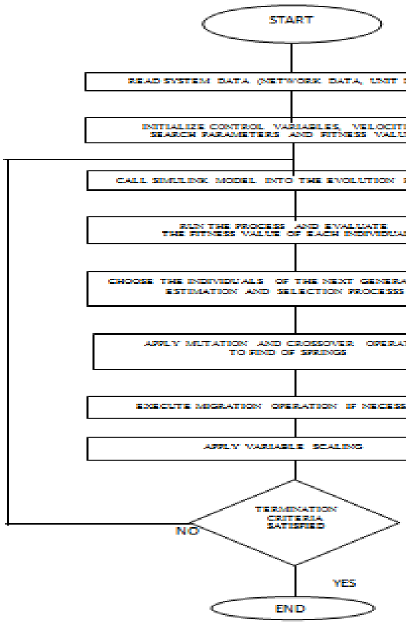


Fig 16: Main calculation procedure for VSHDE

CONTROLLER	% THD	K_P	\ K_I
With PI controller	5.11	0.1	0.01
With Variable Scaling Hybrid Differential Evolution	0.88	1	0.49

Table 1: Relative comparison of sliding mode controller and variable scaling hybrid differential evolution

CONVERGENCE GRAPH

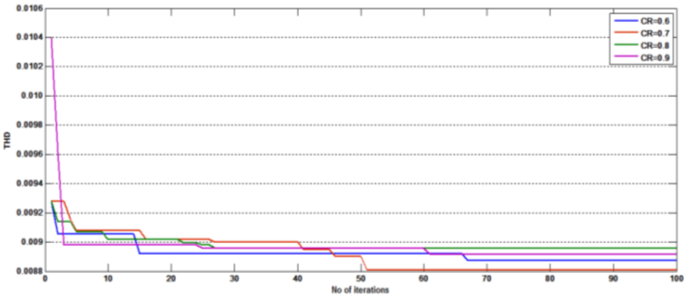


Fig 16: convergence graph

VII. CONCLUSION

The performance presented in this paper makes a significant contribution to the comparative study of the total voltage distortion using the hybrid shunt active filter based on artificial intelligent techniques for different type of filters in order to improve the hybrid shunt active power filter performance and the source current THD values for different filters are shown among all high Butter worth filter has given the best THD values. At this level, comparative studies between the sliding mode controller and variable scaling hybrid differential evolution showed that VSHDE has been proved to be improved in terms of harmonic reduction in source currents. The dc bus voltage has been maintained constant equal to the reference voltage by sliding mode control, variable scaling hybrid differential evolution Optimization controllers. It has been found that these robust and nonlinear controls prove to be better than conventional control.

APPENDIX

PARAMETERS	RATINGS
SUPPLY VOLTAGE Vs	415V
LINE IMPEDENCE Ls	5µH
LINE RESISTANCE Rs	5Ω
INDUCTANCE IN COMPENSATOR Ls	10mH
DC SIDE CAPACITOR	2200µF
DC LINK REFERENCE VOLTAGE	880V

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