Application des Réseaux de Neurones dans la Commande d'un Filtre Actif Parallele en Utilisant Matlab_Simulink

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***Résumé* – Cet article présente un système de commande d'un filtre actif parallèle utilisant deux réseaux de neurones artificielles, l'un remplaçant le contrôleur à hystérésis classique générant les impulsions aux interrupteurs du FAP, l'autre pour la régulation de la tension du bus continu. Les filtres actifs parallèles (FAPs) sont très utilisés dans les applications industrielles pour la compensation des harmoniques de courant générés par les charges non-linéaires en particulier les convertisseurs AC/DC. La configuration habituelle d'un FAP est basée le plus souvent sur un contrôleur à hystérésis pour le pilotage du convertisseur formant le FAP et d'un régulateur PI pour le maintien de la tension continue fixe aux bornes du condensateur de stockage. Avec l'intégration de plus en plus des techniques de contrôle intelligente dans les systèmes d'électronique de puissance, un double contrôleur à base des réseaux de neurones est utilisé pour le contrôle du filtre actif. Les résultats de simulation obtenus en régime permanent en utilisant le Logiciel Matlab_Simulink en association avec le Toolbox SimPowerSystem montrent la faisabilité et les performances de ce double contrôleur utilisant les réseaux de neurones.**

Mots clés – Filtre Actif Parallèle, Charges non-linéaires, Réseaux de neurones artificiels, Distorsion harmoniques

***Abstract*–This paper presents a shunt active filter control system using two artificial neural networks, one replacing the conventional hysteresis controller generates pulses for inverter switches, the other for regulating the DC bus voltage. The shunt active filters (SAF's) are widely used in industrial applications to compensate current harmonics generated by nonlinear loads especially AC/DC converters. The usual configuration of the SAF is based on the hysteresis controller for controlling the converter and a PI regulator for maintaining a fixed voltage across the capacitor storage. With the increasing integration of intelligent control techniques in power electronics systems, a dual-controller based on neural networks is used to control the active filter. The simulation results in steady-state conditions using Matlab_Simulink program in combination with SimPowerSystems Toolbox show the feasibility and performance of the dual controller based an neural networks.**

I. INTRODUCTION

La prolifération des charges non-linéaires utilisant des commandes électronique dans les différentes branches d'une installation industrielle engendre des harmoniques qui ont des effets néfastes sur les équipements et appareillages de contrôle-commande [5]. Ceci nous amène à trouver des solutions pour les compenser. Les solutions traditionnelles à base de filtres passifs ont montré leurs insuffisance d'où la nécessite d'introduire de nouvelles techniques de compensation des harmoniques [1],[2]. Parmi ces solutions on trouve les filtres actifs réalisés autour de convertisseurs d'électronique de puissance ayant l'aptitude de réaliser un filtrage fin et obtenir un courant source presque sinusoïdale. Les performances de ces filtres dépendent de la nature de l'alimentation, le type de la distorsion à compenser, la stratégie de contrôle adoptée, etc…

En fonction de l'application envisagée et de la puissance mise en jeu, on peut utiliser différentes topologies de filtres. Le Filtre Actif Parallèle est considéré comme la solution la plus utilisée pour l'élimination des harmoniques en courant et améliorer ainsi la qualité d'alimentation d'une installation industrielle. Plusieurs travaux ont été réalisés autour du FAP en matière de l'identification des courants harmoniques et de la stratégie de contrôle utilisés qui ont donnés des résultats très satisfaisants. Ces dernières années nous avons assisté à la pénétration et à l'utilisation des techniques de l'intelligence artificielle dans la commande de différents systèmes à base d'électronique de puissance [1],[2],[9],[10],[11],[12], en particulier dans les aspects contrôle et régulation. Les avantages qui motivent l'utilisation des RNAs dans les différents processus de commande et/ou de régulation sont la simplicité d'utilisation, la non nécessité d'avoir un modèle mathématique, la facilité d'apprentissage et plus particulièrement un temps de calcul faible lors d'une implémentation pratique [2].

Cet article présente l'application des réseaux de neurones dans la commande et la régulation de la tension continue d'un filtre actif parallèle en utilisant le Logiciel Matlab_Simulink en association avec le Toolbox SimPowerSystem et ceci en vue de remplacer le contrôleur classique à hystérésis et le régulateur de tension classique PI. Les résultats de simulation obtenus montrent la faisabilité et l'efficacité des réseaux de neurones dans l'imitation des fonctions d'un contrôleur à hystérésis et de régulation de tension en régime transitoire ou permanent avec un courant presque sinusoïdale coté source et un THD respectant les normes standards.

II. FILTRE ACTIF PARALLELE

Le schéma de principe d'un filtre actif parallèle est donné par la Fig.1, la charge non linéaire est formé d'un convertisseur AC/DC alimentée par une source triphasée (v_{sa}, v_{sb}, v_{sc}), l'impédance de la source est représenté par (R_s,L_s). Le filtre actif et constitué d'un convertisseur de tension (VSI), d'une inductance L_f et d'une source de tension continue provenant d'un condensateur C_{dc} alimenté via les diodes antiparallèles du même convertisseur [7].

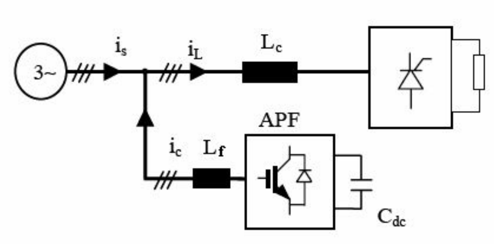

Fig.1 Schéma de principe d'un FAP

II.1 TOPOLOGIE DU CIRCUIT DE PUISSANCE

Différentes topologies sont utilisées pour implémenter le FAP, la configuration standard consiste au PWM-VSI (Pulse Width Modulation Voltage Source Inverter),[6]. L'avantage principale de cette configuration c'est qu'elle ne nécessite qu'un seul élément de stockage comparé au FAP à quatre files ou utilisant un convertisseur multi-niveaux. Les performances du FAP à base d'un VSI afin de compenser la distorsion harmonique dépend de plusieurs paramètres telque la valeur de l'inductance de filtrage L_f, l'élément de stockage de l'énergie C_{dc}, la méthode adoptée pour extraire les courants de référence de compensation ainsi que la technique de contrôle utilisée pour la régulation des trois courants du filtre et de la tension aux bornes de C_{dc} [7],[12].

II.2 MODELE ANALYTIQUE DU FAP-VSI

Les tensions et les courants au point de connexion du FAP dans un repère « abc » sont données par [4]:

$$\begin{aligned} Vsa &= R_f\, i_{fa} + L_f \frac{di_{fa}}{dt} + V_{fa} + V_{MN} \\ Vsb &= R_f\, i_{fb} + L_f \frac{di_{fb}}{dt} + V_{fb} + V_{MN} \\ Vsc &= R_f\, i_{fc} + L_f \frac{di_{fc}}{dt} + V_{fc} + V_{MN} \end{aligned} \quad (1)$$

Les tensions phase-neutre du FAP sont données par :

$$\begin{aligned} V_{f1} &= V_{fa} + V_{MN} \\ V_{f2} &= V_{fb} + V_{MN} \\ V_{f3} &= V_{fc} + V_{MN} \end{aligned} \quad (2)$$

La somme de ces trois tensions donne la tension masse-neutre V_{MN} :

$$V_{MN} = \frac{1}{3}(V_{fa} + V_{fb} + V_{fc}) \quad (3)$$

En remplaçant (3) dans (2) on obtient :

$$\begin{aligned} V_{f1} &= \frac{2}{3}V_{fa} - \frac{1}{3}V_{fb} - \frac{1}{3}V_{fc} \\ V_{f2} &= -\frac{1}{3}V_{fa} + \frac{2}{3}V_{fb} - \frac{1}{3}V_{fc} \\ V_{f3} &= -\frac{1}{3}V_{fa} - \frac{1}{3}V_{fb} + \frac{2}{3}V_{fc} \end{aligned} \quad (4)$$

Ces équations réécrites sous forme matricielle donnent :

$$\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} \quad (5)$$

Les tensions V_{fa}, V_{fb}, V_{fc} peuvent prendre les valeurs 0 ou $\pm V_{dc}$ en dépendance de la fonction de commutation C_k pour la $k^{ième}$ bras du convertisseur $(k = 1, 2, 3)$, C_k est définie comme suit :

$$\begin{aligned} C_k &= 1 \quad if \quad S_k \text{ is } ON \quad and\, S_{k+3} \text{ is } OFF \\ C_k &= 0 \quad if \quad S_k \text{ is } OFF \quad and\, S_{k+3} \text{ is } ON \end{aligned} \quad (6)$$

Par conséquent :

$$\begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} V_{dc} \quad (7)$$

En remplaçant (7) dans (5), les tensions phase-neutre sont données alors par :

$$\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} V_{dc} \quad (8)$$

En utilisant (8), on peut déduire les tensions V_{f1}, V_{f2}, V_{f3} données par le tableau (1).

De même on peut définir l'état de la fonction de commutation d_{nk} définie par :

$$\begin{bmatrix} d_{n1} \\ d_{n2} \\ d_{n3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \quad (9)$$

Dans ce cas, les tensions phase-neutre sont données par la relation suivante:

$$\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \begin{bmatrix} dn1 \\ dn2 \\ dn3 \end{bmatrix} V_{dc} \qquad (10)$$

En remplaçant (10) dans (1) on obtient :

$$L_f \frac{di_{fa}}{dt} = -R_f i_{fa} - d_{n1} V_{dc} + V_{sa}$$
$$L_f \frac{di_{fb}}{dt} = -R_f i_{fb} - d_{n2} V_{dc} + V_{sb} \qquad (11)$$
$$L_f \frac{di_{fc}}{dt} = -R_f i_{fc} - d_{n3} V_{dc} + V_{sc}$$

n	C_1	C_2	C_3	V_{f1}	V_{f2}	V_{f3}
1	0	0	0	0	0	0
2	0	0	1	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$
3	0	1	0	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$
4	0	1	1	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$
5	1	0	0	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$
6	1	0	1	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$
7	1	1	0	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$
8	1	1	1	0	0	0

Tableau (1)

Pour le coté continu du FAP, nous avons l'équation suivante :

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}(2d_{n1} - d_{n1})i_{fa} + \frac{1}{C_{dc}}(d_{n1} + 2d_{n1})i_{fb} \qquad (12)$$

III. COMMANDE DU FILTRE ACTIF PARALLELE

La commande du filtre utilise une technique inspirée de la méthode des courants de référence [3] basé sur la mesure des tensions d'alimentation (V_{sa}, V_{sb}, V_{sc}) et la détermination de l'amplitude du courant maximale à fournir par le filtre I_{smax} donnée par (13):

$$I_{smax} = \frac{2}{3}\frac{P_{moy}}{V_{sm}} \qquad (13)$$

Les courants de référence sont calculés suite à la multiplication de l'image des trois tensions source par le courant I_{smax} . La différence entre ces courants de références avec les courants absorbés par la charge permet de générer les trios courants de compensation (I_{af}, I_{bf} et I_{cf}) :

$$I_{af} = I_{aref} - I_{aL}$$
$$I_{bf} = I_{bref} - I_{bL} \qquad (14)$$
$$I_{cf} = I_{cref} - I_{cL}$$

La Fig.2 donne le schéma bloc du modèle simulink d'extraction des courants de références du FAP.

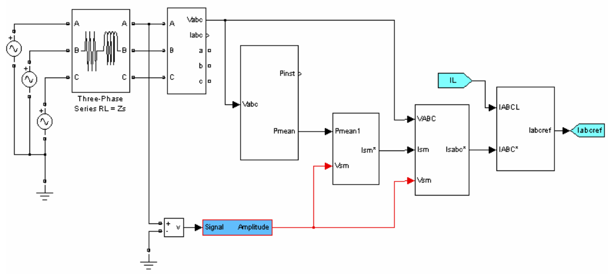

Fig.2 Modèle simulink d'extraction des courants de référence

Nous utilisons pour la commande du convertisseur la technique de modulation à hystérésis caractérisée par une facilité d'implémentation et une grande stabilité, la logique de commutation peut être formulée de la façon suivante [7],[8] :

Si $i_c < i_{cref}$-HB : l'interrupteur supérieur est OFF et l'interrupteur inferieure est ON,

Si $i_c > i_{cref}$+HB : l'interrupteur supérieur est ON et l'interrupteur inferieure est OFF.

Le bloc simulink permettant la génération des signaux de commande du convertisseur est donné par la Fig.3.

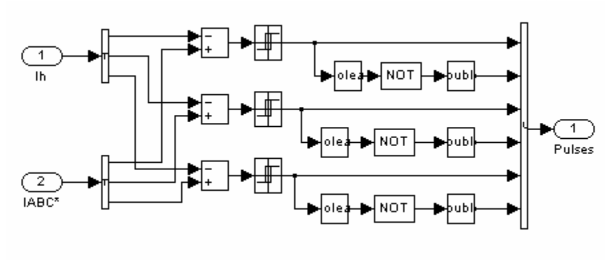

Fig.3 Commande à hystérésis du FAP

IV. CONTROLEUR RNA-FAP

Le système de commande et de régulation à base des réseaux de neurones du filtre actif parallèle utilisé dans ce travail est conçu autour de deux MLPs (Multi-Layer Perceptron). Le premier réseau permet de réguler la tension aux bornes du condensateur C_{dc} afin de la maintenir constante autour d'une valeur de U_{dc}=700V, le deuxième réseau donné par la Fig.4, permet d'imiter le contrôleur classique à hystérésis générant les signaux de commande du convertisseur composant le FAP. L'architecture adoptée pour ce réseau consiste en un MLP trois couches : couche d'entrée correspondant aux entrées $E_{c\text{-}a}$, $E_{c\text{-}b}$, $E_{c\text{-}c}$, une couche caché formé de m neurones et une couche de sortie correspondant aux signaux de commande S_a, S_b, S_c des interrupteurs du demi-pont supérieur du convertisseur. Le nombre des neurones de la couche caché peut être choisi en réalisant plusieurs tests d'apprentissage pour notre cas m=20, certains auteurs utilisent des méthodes intelligentes tel que les algorithmes génétiques pour déterminer ce nombre [1],[8]. L'apprentissage de ce réseau est réalisé avec l'algorithme de retro-propagation Levenberg-Marquardt en utilisant 10000 exemples d'apprentissage (off-line) obtenu par simulation. Cette méthode est recommandée dans le cas ou la fonction performance "Mean square error" est utilisée [2]. Les neurones de cette couche utilisent la fonction Sigmoïde alors que pour les neurones de la couche de sortie la fonction linéaire.

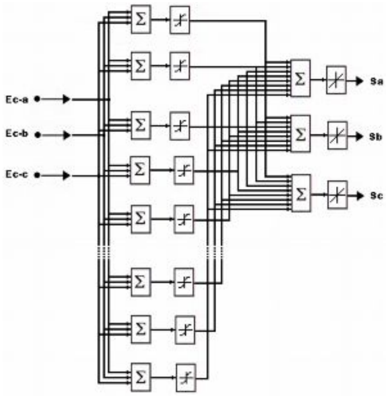

Fig.4 Structure du contrôleur RNA_FAP

Le schéma bloc du filtre actif à base de deux contrôleurs à RNAs est donné par la Fig.5.

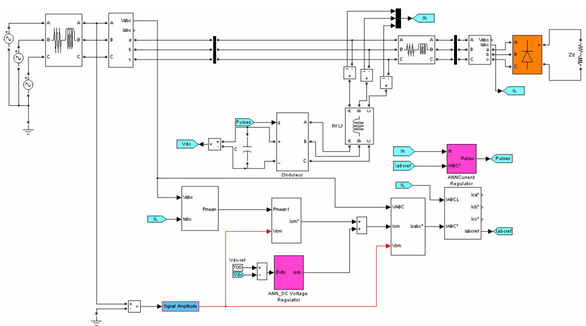

Fig.5 FAP à base de contrôleurs à RNAs

V. SIMULATIONS

Les travaux de simulation sont élaborés en utilisant le Logiciel Matlab_Simulink et le Toolbox SimPowerSystem en considérant le cas d'une source d'alimentation triphasée équilibré alimentant une charge (R_{ch},L_{ch}) à travers un pont à diodes triphasé. L'avantage principal qui motive l'utilisation de cet outil de simulation est sa capacité d'intégrer dans un même modèle le bloc commande et la structure de puissance à simuler. Les paramètres utilisés pour la simulation sont donnés par le tableau (2).

Source	Tension V_s = 220 V Fréquence F_s = 50 Hz Resistance R_s = 0.1mΩ Inductance L_s = 0.0002 mH
Charge non-linéaire	Resistance R_{ch} = 48.6 Ω Inductance L_{ch} = 40 mH
Filtre actif parallèle	Tension U_{dc} = 700 V Capacité C_{dc} = 1100 µF Resistance R_c = 0.27 m Ω Inductance L_c = 0.8 mH

Tableau (2)

La Fig.6 montre le courant de la source en absence du filtrage, ce courant n'est pas sinusoïdale est riche en harmoniques avec un THD de 27.72%.

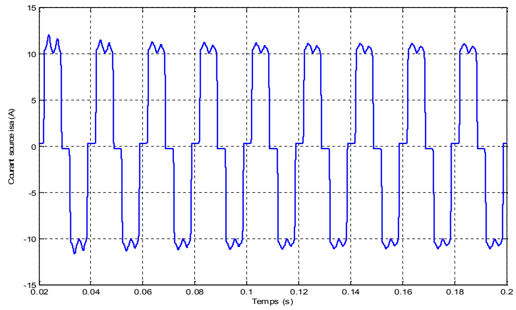

Fig.6 Courant source sans FAP

Le spectre des harmoniques correspondant est donné par la Fig.7.

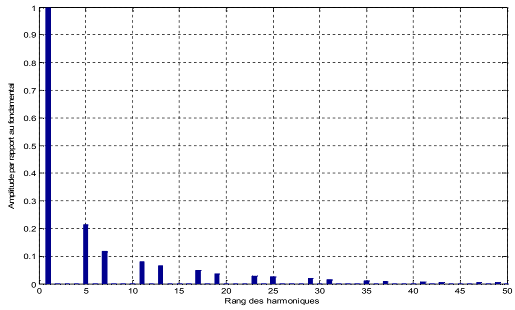

Fig.7 Spectre des harmoniques sans FAP

La Fig.8 et la Fig.9 donnent le courant source et son spectre après filtrage. Ce courant est sinusoïdal avec un THD nettement réduit, environ 1.49%.

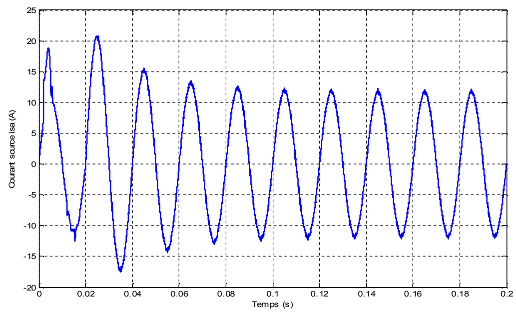

Fig.8 Courant source avec FAP

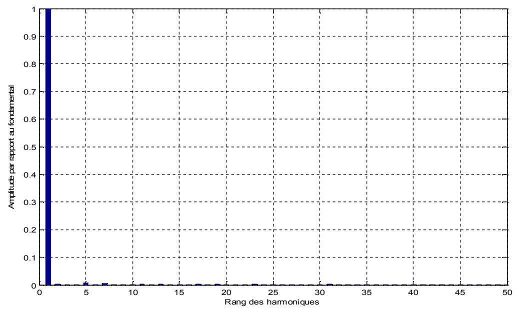

Fig.9 Spectre des harmoniques du courant source avec FAP

La Fig.10 donne l'allure de la tension aux bornes du condensateur de stockage. Au départ le condensateur est chargé par une tension Vi=500V, la tension suit parfaitement sa valeur de référence Vdc=700V stabilisée à l'instant t=0.13sec.

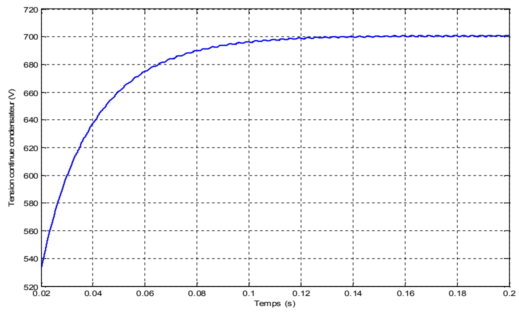

Fig.10 Tension continue Vdc

La tension et le courant source après filtrage sont données par la Fig.11, le courant et en phase avec la tension.

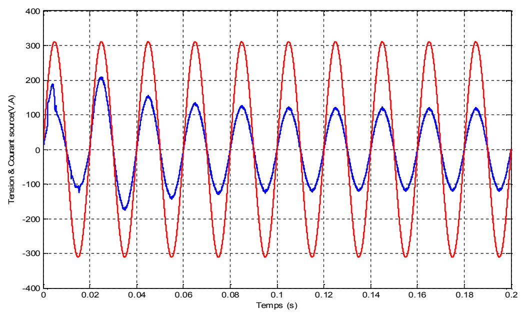

Fig.11 Tension et Courant source avec FAP

Les performances du double contrôleur proposé pour la commande et la régulation de la tension du bus continu du filtre actif parallèle en terme d'élimination des harmoniques sont très satisfaisantes, par analyse du spectre, on constate que le THD du courant source passe de 27.72% à 1.49% ce qui respecte énormément les normes standards IEEE519 & IEC61000.

VI. CONCLUSION

La commande d'un filtre actif parallèle en utilisant deux contrôleurs à base des RNAs est présentée dans cet article. La technique de commande adoptée utilise une stratégie de contrôle en courant. Le modèle de base développé nous à permet de construire la base de données nécessaire à l'apprentissage des deux réseaux de neurones. Les deux contrôleurs utilisent une architecture conçue autour de deux MLP (Multi-Layer Perceptron). Les résultats de simulation obtenus en utilisant le Logiciel Matlab_Simulink et le Toolbox SimPowerSystem montrent la faisabilité de l'approche suivie et permettent de conclure sur l'importance de cette technique d'intelligence artificielle dans la commande du convertisseur composant un filtre actif. Le THD obtenu après filtrage est de 1.49% respectant ainsi les normes standards internationales IEEE 519 & IEC61000.

VII. REFERENCES

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Utilisation des Reseaux de Neurones dans l'Implementation de la Technique de Commande SVPWM sous Matlab-Simulink

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***Résumé*— Cet article présente l'étude, la modélisation et la simulation de la technique de commande SVPWM à base des réseaux de neurones artificiels en utilisant le Logiciel MATLAB_Simulink. C'est l'une des techniques les plus avancée de contrôle en PWM (Pulse Width Modulation), elle peut être utilisée pour la commande des machines électriques afin d'avoir des performances dynamiques plus meilleurs ou pour le contrôle d'un filtre actif de puissance utilisé pour éliminer les harmoniques coté source. Dans une première partie, nous avons présenté le principe de la SVPWM poursuivi de l'établissement d'un modèle de simulation. Ensuite nous avons présenté l'architecture du contrôleur SVPWM_ANN qui est un MLP (Multi-Layer Perceptron). Il reçoit les entrées SXYZ et génère à sortie les signaux de commande au convertisseur de tension deux niveaux. Ce contrôleur a pour avantage principal la réduction du nombre de calcul en particulier pour les fonctions trigonométriques utilisées pour la détermination des temps T_k et T_{k+1}. Pour tester la faisabilité et la fonctionnalité du contrôleur SVPWM_ANN, nous avons élaboré différentes simulations. Les résultats obtenus sont très satisfaisantes.**

Mots clés—ANN-SVPWM, Convertisseur de Tension deux Niveaux, Réseaux de Neurones Artificiels, Multi-Layer Perceptron

***Abstract*—This paper presents the design, modeling and simulation of the SVPWM control technique based on artificial neural networks using MATLAB_Simulink program. It is one of the most advanced PWM (Pulse Width Modulation) techniques control, it can be used to control electrical machines in order to have better dynamic performance or control an active power filter to eliminate current harmonics in source side. In the first part, we have presented the principle of SVPWM pursued with establishment of a simulation model. In second part, we have presented the architecture of the SVPWM_ANN's controller based an MLP (Multi-Layer Perceptron) network. The ANN receives inputs and generates SXYZ output control signals to the two levels voltage source. The major advantage of proposed controller is reduction of the calculation number especially for trigonometric functions used to determine T_k and T_{k+1} times. To test the feasibility and functionality of the SVPWM_ANN's controller, we have developed different simulations. The results obtained are very satisfactory.**

I. INTRODUCTION

La machine asynchrone est largement utilisée dans les applications industrielles, pour la plupart des processus elle nécessite la vitesse variable [1]. Ces performances sont dégradées aux basses vitesses et influencée par la présence des ondulations dans le couple [2]. Différentes techniques de génération des signaux de commande ont été utilisées pour le contrôle du convertisseur de puissance qui alimente la machine, mais la plus importante est la SVPWM (Space Vector Pulse Width Modulation), elle offre des performances plus meilleurs que les autres techniques [3],[4].

L''inconvénient majeure de la SVPWM est les temps de calcul énormes nécessaire à son implémentation due aux fonctions trigonométriques utilisées pour la détermination des temps T_k et T_{k+1} d'où l'intérêt d'utiliser les réseaux de neurones. Les applications des RNAs dans le domaine de l'électronique de puissance à connu ces dernières années une grande pénétration en particulier le MLP FeedForward qui peut implémenter n'importe quelle fonction non-linéaire [6].

Cet article présente la modélisation et la simulation de la technique de contrôle SVPWM classique en vue de l'implémenter avec un réseau de neurones artificiels en utilisant le Logiciel MATLAB_Simulink, ceci afin de l'utiliser pour la commande des machines électriques ou le contrôle du convertisseur d'un filtre actif parallèle. Afin de tester la faisabilité du contrôleur SVPWM-ANN différentes simulations ont été réalisées, les résultats obtenus concordent parfaitement avec ceux obtenus avec un contrôleur SVPWM classique.

II. PRINCIPE DE LA SVPWM

La tension de référence statorique pour un moteur asynchrone peut être définie par :

$$U_s = 2(V_{AN} + V_{BN} e^{j2\pi/3} + V_{CN} e^{j4\pi/3})/3 \quad (1)$$

Avec (V_{AN}, V_{BN}, V_{CN}) sont les tensions de phase. Le convertisseur de tension triphasé pouvant alimenter la machine asynchrone est représenté par la Fig.1, il est constitué de six interrupteurs IGBTs.

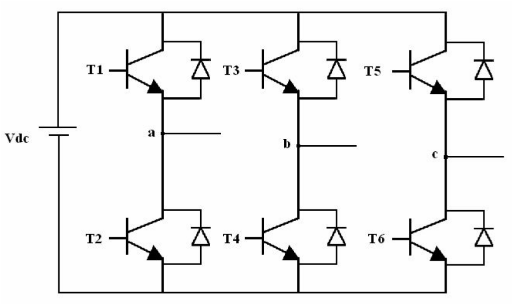

Fig.1 Convertisseur de tension triphasé

Ce convertisseur possède huit états de fonctionnement donnés par la Fig.2.

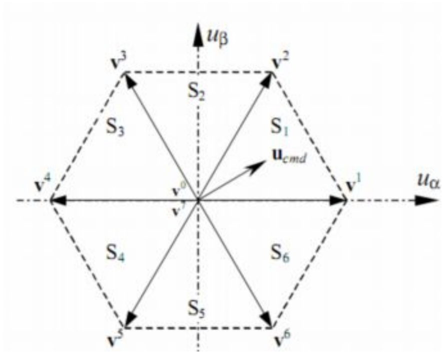

Fig.2 Vecteur espace d'état

Pour chaque période de commutation, le vecteur tension de sortie U_s peut être calculé en utilisant les deux vecteurs tensions adjacents de la façon suivante :

$$U_s = T_k U_{sk} / T + T_{k+1} U_{sk+1} / T + T_o U_{ooo/T} + T_7 U_{777} / T \qquad (2)$$

Ou T est la période d'échantillonnage, T_k , T_{k+1} sont respectivement le temps d'application de U_{sk} et de U_{sk+1}, de même T_o ,T_7 sont le temps d'opération de U_{ooo} et de U_{777}.

Avec U_{ooo} et U_{777} sont les deux vecteurs tensions nul.

III. ALGORITHME DE LA SVPWM

Selon la Fig.2, U_s et T sont dans le premier secteur, ils peuvent être écrites sous la forme :

$$U_s = T_1 U_o / T + T_3 U_{60} / T \qquad (3)$$
$$T = T_1 + T_3 + T_o$$

Ou T est la période du signal PWM, T_1 et T_3 sont respectivement les temps d'application de U_o et de U_{60}.

Les vecteurs tensions V_α et de V_β du vecteur tension sortie U_s dans le plan $(\alpha - \beta)$ sont données par les expressions suivantes :

$$V_\alpha = T_1 U_o / T + T_3 U_{60} \cos(\pi/3) / T \qquad (4)$$
$$V_\beta = T_3 U_{60} \sin(\pi/3) / T$$

D'après l'équation (1), nous avons :

$$U_o = U_{6o} = 2Vdc/3$$

Dans ce cas les vecteurs tensions V_α et V_β peuvent être écrites sous la forme :

$$T_1 = 3TV_\alpha / 2V_{dc} - \sqrt{3}TV_\beta / 2V_{dc}$$
$$T_3 = \sqrt{3}TV_\beta / V_{dc} \qquad (5)$$
$$T_o = T - T_1 - T_3$$

On peut généraliser les temps d'opération T_k , T_{k+1} correspondant à U_{sk} et de U_{sk+1} dans les autres secteurs par :

$$T_k = (\sqrt{3}T / V_{dc})[V_\alpha \sin(k\pi/3) - V_\beta \cos(k\pi/3)] \qquad (6)$$
$$T_{k+1} = (\sqrt{3}T / V_{dc})[V_\beta \cos((k-1)\pi/3) - V_\alpha \sin((k-1)\pi/3)]$$

IV. MODELE SIMULINK DE LA SVPWM

1er Etape : Détermination des tensions de références V_α, V_β :

$$\begin{cases} V_1 = V.\sqrt{2}.\sin(\omega.t) \\ V_2 = V.\sqrt{2}.\sin(\omega.t - 2.\pi/3) \\ V_3 = V.\sqrt{2}.\sin(\omega.t + 2.\pi/3) \end{cases} \qquad (7)$$

$$\begin{cases} V\alpha = \sqrt{3}.(2V_1 - V_2 - V_3) \\ V\beta = \frac{3}{4}.(V_2 - V_3) \end{cases} \qquad (8)$$

Le bloc simulink calculant V_α et V_β est donné par la Fig.3.

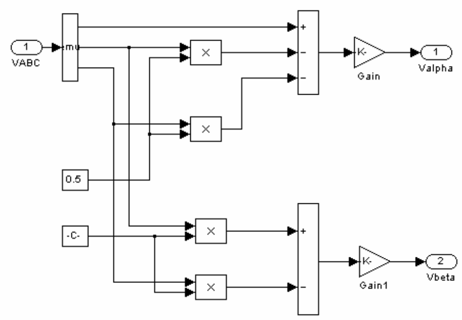

Fig.3 Bloc simulink calculant V_α et V_β

2ème Etape : Détermination du secteur de U_s :

Soient les grandeurs tensions intermédiaires B_0, B_1, B_2, ils peuvent être calculés en utilisant les deux composantes V_α et de V_β donnés par (9), le secteur est déterminé en fonction de P calculé selon (10) et en utilisant le tableau (1).

$$\begin{cases} B_0 = V_\beta \\ B_1 = +\sin(\pi/3)V_\alpha - \sin(\pi/6)V_\beta \\ B_2 = -\sin(\pi/3)V_\alpha - \sin(\pi/6)V_\beta \end{cases} \quad (9)$$

Connaissant B_0, B_1, B_2, il est possible de calculer le secteur [5] dans le quel est localisé le vecteur U_s selon (10) :

$$P = 4.B_o + 2.B_1 + B_2 \quad (10)$$

$$\begin{cases} Si \ \mathrm{B_i} \geq 0 \ \Rightarrow \ 1 \\ \text{Si non} \ \Rightarrow \ 0 \end{cases} \qquad i \in \{0,1,2\}$$

P	1	2	3	4	5	6
Secteur	2	6	1	4	3	5

Tableau (1) Relation entre P et le Secteur S

Le bloc simulink calculant le secteur S en fonction de B_0, B_1, B_2 est donné par la Fig.4.

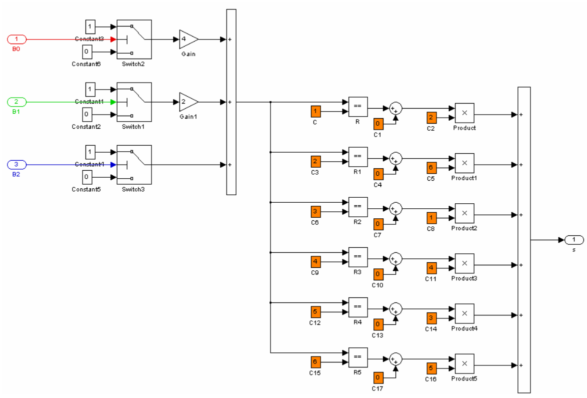

Fig.4 Bloc calculant le secteur S

3ème Etape : Calcul de des temps intermédiaires X, Y, Z :

$$\begin{cases} X = \dfrac{T}{V_{dc}}\sqrt{3}V_\beta \\ Y = \dfrac{T}{V_{dc}}.(\dfrac{\sqrt{3}}{2}V_\beta + \dfrac{3}{2}V\alpha) \\ Z = \dfrac{T}{V_{dc}}.(\dfrac{\sqrt{3}}{2}V_\beta - \dfrac{3}{2}V\alpha) \end{cases} \quad (11)$$

Le modèle simulink permettant de calculer les temps X, Y, Z est donné par la Fig.5.

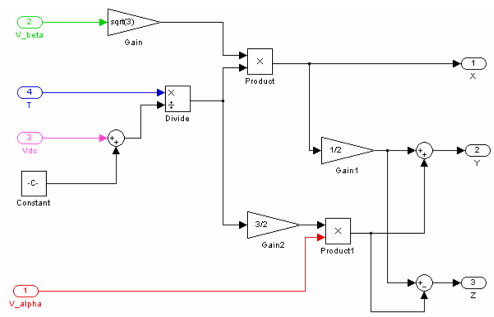

Fig.5 Bloc simulink calculant X, Y, Z

4ème Etape : Calcul des Temps T_1 et T_2 :

Pour chaque secteur, le calcul de T_1 et T_2 se fait en fonction de X, Y, Z selon le tableau (2). La Fig.6 donne le schéma simulink implantant le bloc calculant T_1 et T_2.

Secteur	1	2	3	4	5	6
T1	-Y	Z	X	Y	-Z	-X
T2	Z	X	Y	-Z	-X	-Y

Tableau (2)

5ème Etape : Génération des signaux de modulation T_a, T_b et T_c :

$$\begin{cases} T_a = (T - T_1 - T_2)/4 \\ T_b = T_a + T_1/2 \\ T_c = T_b + T_2/2 \end{cases} \quad (12)$$

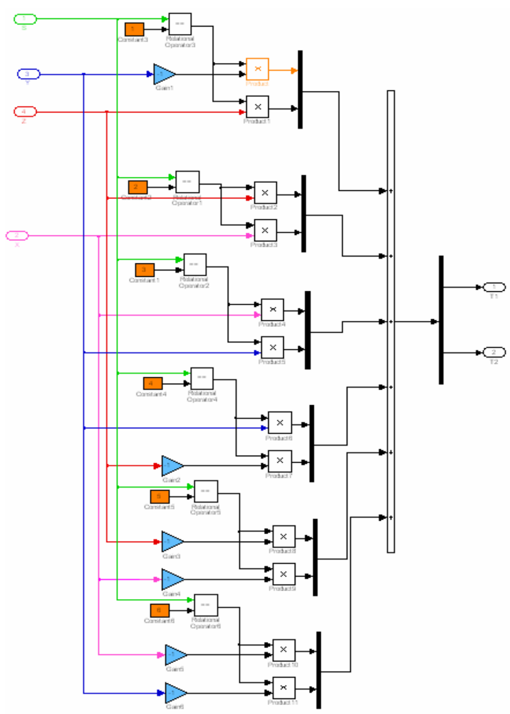

Fig.6 Bloc simulink calculant les temps T_1 et T_2

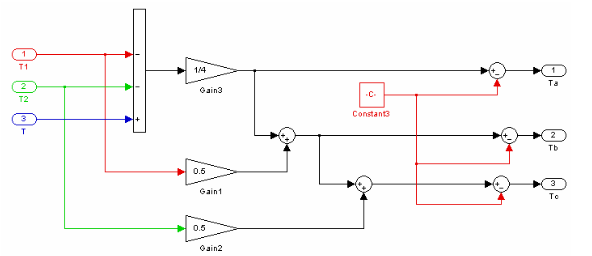

Fig.7 Bloc Simulink générant les signaux de modulation

$6^{ème}$ Etape : Génération des signaux T_{cm1}, T_{cm2} et T_{cm3} :

	S1	S2	S3	S4	S5	S6
Tcm1	Ta	Tb	Tb	Tc	Tb	Tb
Tcm2	Tb	Tb	Ta	Tb	Tb	Tc
Tcm3	Tb	Tc	Tb	Tb	Ta	Tb

$7^{ème}$ Etape : Génération des signaux de commande:

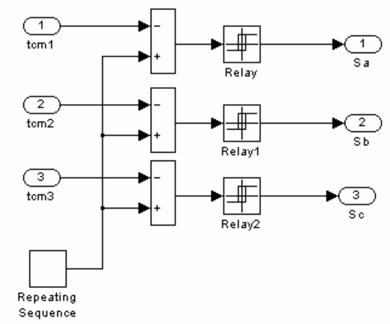

Fig.8 Bloc simulink générant les signaux de commande

V. Reseaux de neurones-SVPWM

Les équations calculant T_k et T_{k+1} données par (6) utilisent des fonctions trigonométriques complexes qui nécessitent des calculs énormes [6]. L'utilisation d'un réseau de neurones peut réduire énormément ce temps. Le schéma bloc du contrôleur ANN-SVPWM développé est donné par la Fig.9, il permet d'imiter et de remplacer tous les blocs utilisés dans la SVPWM classique. L'architecture adoptée pour ce réseau consiste en un MLP quatre couches : une couche d'entrée correspondant aux entrées SXYZ, deux couches cachées formé de 12 et 20 neurones respectivement, une couche de sortie correspondant aux signaux de sortie T_{cm1}, T_{cm2} et T_{cm3}. Le nombre des neurones de la couche caché peut être choisi en réalisant plusieurs tests d'apprentissage, certains auteurs utilisent des méthodes intelligentes tel que les algorithmes génétiques pour déterminer ce nombre [7],[8], pour notre cas, nous avons utilisés plusieurs tests. L'apprentissage de ce réseau est réalisé avec l'algorithme de retro-propagation Levenberg-Marquardt en utilisant 20000 exemples d'apprentissage (off-line) obtenu par simulation. Cette méthode est recommandée dans le cas ou la fonction performance "Mean square error" est utilisée [8]. Les neurones des couches cachés utilisent la fonction Sigmoïde alors que pour les neurones de la couche de sortie la fonction linéaire. La Fig.9 donne le bloc simulink du contrôleur SVPWM_ANN.

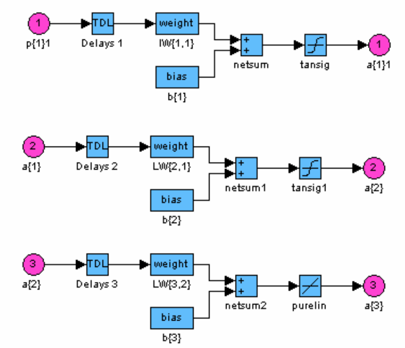

Fig.9 SVPWM_ANN

La Fig.10 présente le schéma bloc de la SVPWM implémentée en utilisant les réseaux de neurones artificiels.

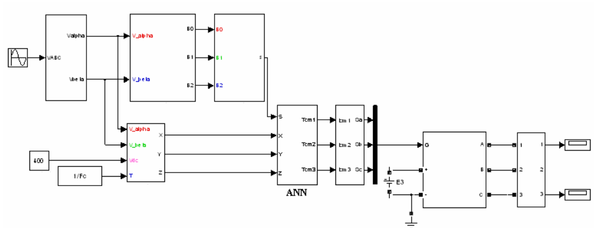

Fig.10 Schéma Bloc simulink de la SVPWM-ANN

VI. Simulations

Les travaux de simulation sont élaborés en utilisant le Logiciel Matlab_Simulink dans le cas d'un convertisseur de tension triphasé à deux niveaux.

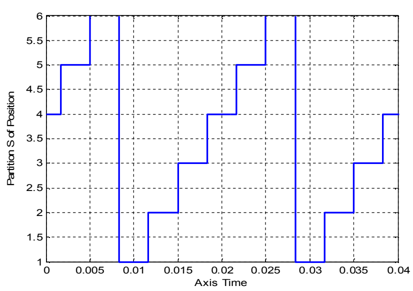

Fig.11 Secteur S

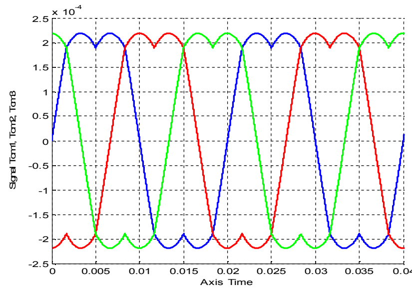

Fig.12 Signaux de modulation T_{cm1}, T_{cm2}, T_{cm3}

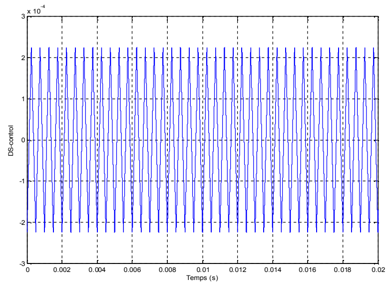

Fig.13 Signal de référence V_{car}

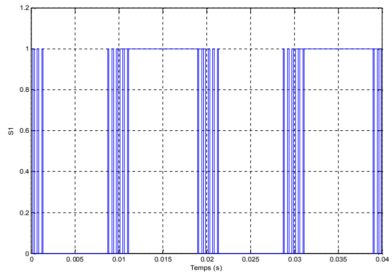

Fig.14 Signal de commande S_1

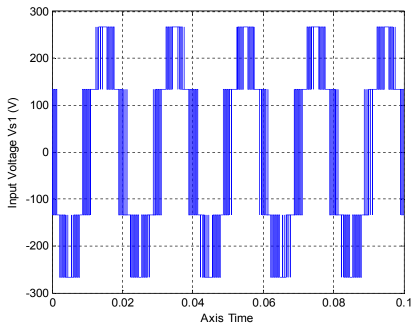

Fig.15 Tension de phase V_{AN}(V)

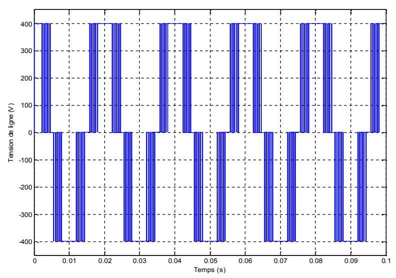

Fig.16 Tension de ligne U_{AB}(V)

Fig.11 et Fig.12, présentent respectivement l'évolution du secteur S et les trois signaux de modulation T_{cm1}, T_{cm2}, T_{cm3}. La Fig.13, montre le signal triangulaire qui doit être comparé avec les trois modulantes afin d'obtenir les signaux de commande pilotant le convertisseur, dont on représente S_1 à la Fig.14. La Fig.15 et la Fig.16, montrent les allures de la tension de phase V_{AN}(V) et de la tension de ligne U_{AB}(V) qui sont identiques à ceux qui peuvent être obtenu en utilisant la technique SVPWM classique. Les résultats de simulation numérique obtenus permettent en mettre en évidence la faisabilité et les performances du système de commande à base d'un contrôleur ANNs-SVPWM.

VII. Conclusion

Un modèle de la technique de commande SVPWM est élaboré en utilisant le Logiciel MATLAB-Simulink. Nous l'avons utilisé pour la commande d'un convertisseur de tension à deux niveaux, les résultats obtenus par simulation coïncident parfaitement avec ceux obtenus avec la SVPWM classique. Afin de simplifier ce modèle et réduire les opérations de calcul, nous avons conçu un contrôleur SVPWM à base de réseaux de neurones capable d'imiter et de reproduire fidèlement les mêmes fonctions du système conventionnel. L'apprentissage de ce réseau est réalisé avec l'algorithme de retro-propagation Levenberg-Marquardt en utilisant 20000 exemples d'apprentissage (off-line) obtenu par simulation. Dans un travail futur ce contrôleur sera utilisé pour la commande d'une machine asynchrone et pour le contrôl du convertisseur composant un filtre actif parallèle de puissance en vue d'évaluer ces performances en régime transitoire et permanent.

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Fuzzy Logic Current Controller for Shunt Active Filter to Compensate Harmonic Currents Based on ANN DC Voltage Regulator

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***Abstract* –This paper presents a three-phase three-wire shunt active filter using a fuzzy current controller to compensate harmonic currents perturbations under ideal voltages conditions. The control strategy used is based on the synchronous reference frame detection method. The advantage of fuzzy current controller proposed in this paper that it is based on linguistic description, does not require an accurate mathematical model and can work with imprecise inputs. Furthermore the fuzzy control rules can be modified automatically and instantaneously, which can improve the dynamic performance of the system. The dc voltage capacitor is controlled by ANN regulator to maintain it constant. The numerical simulation results, using MATLAB-Simulink and Power System BlockSet Toolbox, from complete structure including control and power circuits are presented and discussed.**

***Keywords*—** Shunt active filter, Fuzzy current controller, ANN dc voltage regulator, Harmonic currents compensation, synchronous reference frame detection method.

I. INTRODUCTION

With the proliferation of nonlinear power electronics loads, the problem of harmonic is severity, which influences the power quality of power grid. Passive power filter is a traditional harmonic restraint method. The passive filtering is a simple way to eliminate the harmonic currents. However, it does not allow to completely eliminating all of them and has many drawbacks such as series or parallel resonance with the system impedance [1].

Active filter is used, these last years, to improve power quality on the load side from the grid current, by injecting compensating currents [2]. The performance of an active filter mainly depends on the reference current generation strategy, hysteresis or PWM control, topology of the power converter, etc…

Conventionally, passive LC filters were used to eliminate line harmonics. However the passive filters have the demerits of fixed compensation. The recent advances in power semiconductor devices have resulted. Various topologies of active filters have been proposed, the voltage source inverter (VSI) structure is most used.

In recent years, fuzzy logic and ANN controllers have generated a great deal of interest in certain applications [5], [6]. The advantages of these controllers are: robustness, no need to accurate mathematical model, can work with imprecise inputs and can handle non-linearity.

In this paper, fuzzy logic current controller associated with ANN dc voltage regulator are proposed to control a three-phase shunt active filter based on the synchronous reference frame detection method to compensate harmonic currents.

The performance of shunt active filter based on fuzzy current controller and ANN dc voltage regulator under balanced voltages source for steady-state conditions are evaluated using Matlab-Simulink and power system BlockSet Toolbox, from complete structure including control and power circuits. The obtained results showed that, the proposed shunt active filter control scheme produced a sinusoidal supply current with acceptable low harmonic distortion and in the phase with the line voltage.

II. SHUNT ACTIVE FILTER

II.1 POWER CIRCUIT

The basic block diagram including non linear load compensation principle of a shunt active power filter is shown in Fig.1. It is controlled to draw/supply a compensated current from/to the utility, such that it cancels harmonic currents of the non-linear load and makes the source current in phase with the different waveforms. The current drawn from the power system at the coupling point of the shunt APF will result sinusoidal [7],[8].

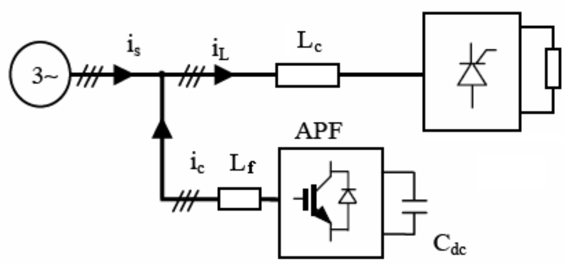


Figure.1 Shunt active filter

II.2 SHUNT ACTIVE FILTER MODEL

The voltages at the connection point of the shunt active power filter leads to the following equations in the "abc" frame [3],[4]:

$$
\begin{aligned}
Vsa &= R_f\, i_{fa} + L_f \frac{di_{fa}}{dt} + V_{fa} + V_{MN} \\
Vsb &= R_f\, i_{fb} + L_f \frac{di_{fb}}{dt} + V_{fb} + V_{MN} \\
Vsc &= R_f\, i_{fc} + L_f \frac{di_{fc}}{dt} + V_{fc} + V_{MN}
\end{aligned}
\qquad (1)
$$

The neutral-to-phase active power filter voltages are given by:

$$
\begin{aligned}
V_{f1} &= V_{fa} + V_{MN} \\
V_{f2} &= V_{fb} + V_{MN} \\
V_{f3} &= V_{fc} + V_{MN}
\end{aligned}
\qquad (2)
$$

Summing the three equations in (2) the masse-to-neutral voltage V_{MN} is given by:

$$V_{MN} = \frac{1}{3}(V_{fa} + V_{fb} + V_{fc}) \qquad (3)$$

By substituting (3) in (2), we can obtain:

$$
\begin{aligned}
V_{f1} &= \frac{2}{3}V_{fa} - \frac{1}{3}V_{fb} - \frac{1}{3}V_{fc} \\
V_{f2} &= -\frac{1}{3}V_{fa} + \frac{2}{3}V_{fb} - \frac{1}{3}V_{fc} \\
V_{f3} &= -\frac{1}{3}V_{fa} - \frac{1}{3}V_{fb} + \frac{2}{3}V_{fc}
\end{aligned}
\qquad (4)
$$

The equations (4) can be written in a matrix form:

$$
\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} \qquad (5)
$$

The voltages V_{fa}, V_{fb}, V_{fc} take the value 0 or $\pm V_{dc}$ depending on the switching function C_k of the $k^{ième}$ inverter leg $(k = 1, 2, 3)$, C_k which is defined as, follows:

$$
\begin{aligned}
C_k &= 1 \quad if \quad S_k \; is \; ON \quad and\, S_{k+3} \; is \; OFF \\
C_k &= 0 \quad if \quad S_k \; is \; OFF \quad and\, S_{k+3} \; is \; ON
\end{aligned}
\qquad (6)
$$

Hence,

$$
\begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} V_{dc} \qquad (7)
$$

By substituting (7) in (5) the neutral-to-phase voltages are expressed by:

$$
\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} V_{dc} \qquad (8)
$$

Using (8), the eight possible values of the voltages V_{f1}, V_{f2}, V_{f3} can be deduced in table I, note that n is the number of the switching states.

Furthermore, a switching state function d_{nfk} can be defined as:

$$
\begin{bmatrix} d_{n1} \\ d_{n2} \\ d_{n3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \qquad (9)
$$

Dans ce cas, les tensions phase-neutre sont données par la relation suivante:

$$
\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \begin{bmatrix} d_{n1} \\ d_{n2} \\ d_{n3} \end{bmatrix} V_{dc} \qquad (10)
$$

By substituting (10) in (1) and taking into account the relation (1) the following equations hold:

$$
\begin{aligned}
L_f \frac{di_{fa}}{dt} &= -R_f\, i_{fa} - d_{n1}V_{dc} + V_{sa} \\
L_f \frac{di_{fb}}{dt} &= -R_f\, i_{fb} - d_{n2}V_{dc} + V_{sb} \\
L_f \frac{di_{fc}}{dt} &= -R_f\, i_{fc} - d_{n3}V_{dc} + V_{sc}
\end{aligned}
\qquad (11)
$$

On the dc side of the APF circuit the following equation holds:

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}(2d_{n1} - d_{n1})i_{fa} + \frac{1}{C_{dc}}(d_{n1} + 2d_{n1})i_{fb} \qquad (12)$$

n	C_1	C_2	C_3	V_{f1}	V_{f2}	V_{f3}
1	0	0	0	0	0	0
2	0	0	1	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$
3	0	1	0	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$
4	0	1	1	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$
5	1	0	0	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$
6	1	0	1	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$
7	1	1	0	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$
8	1	1	1	0	0	0

Table (1)

III. CONTROL STRATEGY

The control strategy to compensate harmonic currents used in this work is based on the synchronous reference frame detection method. The principle of this technique is described below [9]. The three phase currents i_a, i_b and i_c are transformed from three phase (abc) reference frame to two phase's $(\alpha - \beta)$ stationary reference frame currents i_α and i_β using:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (13)$$

Using a PLL (Phase Locked Loop), we can generate $\cos(\theta_{est})$ and $\sin(\theta_{est})$ from the phase voltage source v_{sa}, v_{sb}, v_{sc}.

The currents expression i_α and i_β in $(d-q)$ reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (14)$$

The DC quantities and all other harmonics are transformed to non DC quantities using a low pass filter:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \qquad (15)$$

The expression of the reference current $i_{\alpha-ref}$ and $i_{\beta-ref}$ are given by:

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (16)$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \qquad (17)$$

The reference currents in the (abc) frame is given by:

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \qquad (18)$$

Finally, the compensation currents (i_{ca}, i_{cb} and i_{cc}) are given by:

$$\begin{aligned} i_{ca} &= i_{a-ref} - i_{La} \\ i_{cb} &= i_{b-ref} - i_{Lb} \\ i_{cc} &= i_{c-ref} - i_{Lc} \end{aligned} \qquad (19)$$

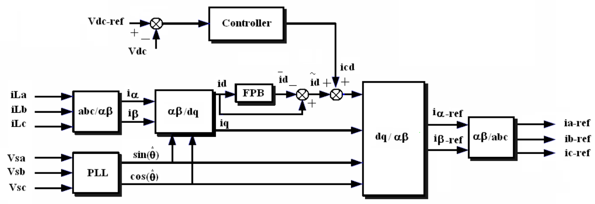


Figure.2 Basic Synchronous Reference Frame

The PLL is used to detect the zero crossing points of the utility voltages in non ideal conditions. The drawback with this technique is that these points not be exactly detected if the signal contains high frequency perturbation [10].

IV. DC VOLTAGE CONTROLLER

A. *PI VOLTAGE REGULATOR*

The regulation loop consists of the comparison of the measured voltage with the reference voltage, admitting that the function of the system to be controlled is given by [11]:

$$\frac{V_s^2}{(V_{dc-ref}.C_{dc}.s)} \qquad (20)$$

The closed loop transfer function using a PI regulator is given by:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{(K_p + K_i/s).(V_s^2/(V_{dc-ref}.C_{dc}.s))}{1+(K_p + K_i/s).(V_s^2/(V_{dc-ref}.C_{dc}.s))} \qquad 21)$$

The development of this equation gives:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{\frac{K_p.V_s^2}{V_{dc-ref}.C_{dc}}.s + \frac{K_i}{V_{dc-ref}.C_{dc}}}{s^2 + \frac{K_p.V_s^2}{V_{dc-ref}.C_{dc}}.s + \frac{K_i.V_s^2}{V_{dc-ref}.C_{dc}}} \qquad (22)$$

A second order characteristic equation of the closed loop system is deduced:

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0 \qquad (23)$$

Where:

$$\omega_n = \sqrt{\frac{K_i.V_s^2}{V_{dc-ref}.C_{dc}}}, \quad \xi = \frac{K_p.V_s}{2\sqrt{K_i.V_{dc-ref}.C_{dc}}} \qquad (24)$$

From (11) the proportional and integrator coefficient K_p, K_i of the controller can be deduced:

$$K_p = \frac{2.\xi.K_i}{\omega_n}, \quad K_i = \frac{\omega_n^2 V_{dc-ref}.C_{dc}}{V_s^2} \qquad (25)$$

The expression of the current I_{sc} to compensate the inverter losses and maintain the constant dc-link voltage is given by:

$$I_{sc} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \qquad (26)$$

To obtain optimal dynamic performance for the system, the value of the damping ration ξ must be equal a 0.707.

B. ANN'S DC VOLTAGE REGULATOR

The dc voltage neutral network controller used is presented in Fig.3. Its role is to maintain constant voltage around a desired value Vdc-ref = 700V. The input pattern of the network is the error values EVdc between the measured dc voltage Vdc-mes and its reference value Vdc-ref. and its output is the current to compensate inverter losses. The architecture adopted for this network is three layer perceptron, the hidden layer contains one neuron with tansig activation function, whereas the output layer contains one neuron with linear activation function.

The network was trained with back propagation Levenberg-Marquardt algorithm using 20,000 examples of learning (off-line) obtained by simulation-based on PI control loop.

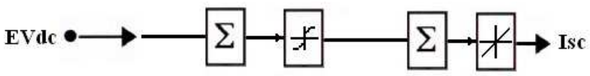
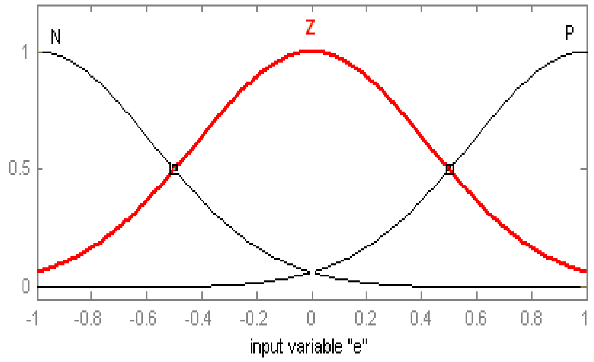


Figure.3 DC voltage ANN controller

V. FUZZY CURRENT CONTROLLER

The main component of an active filter is the current controller. Generally the classical hysteresis controller is used to generate pulses to the PWM inverter; it is very stable and generates a minimum noise.
Recently, fuzzy logic controllers (FLCs) have been interest a good alternative in more application. The advantage of fuzzy systems are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, and they are more robust than conventional nonlinear controllers [12].

Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. To develop the rules of the fuzzy logic, we need good understand of the process to be controlled, but it does not require a complicated mathematical model. The desired switching signals for the filter inverter circuit are determined according to the error in the filter current. In this case, the fuzzy logic current controller has two inputs, named error *e* and change of error *de* and one output named *s*. Here the error *e* and change of error *de* are the input variable for the system. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig. 4 shows the membership functions used in fuzzification.



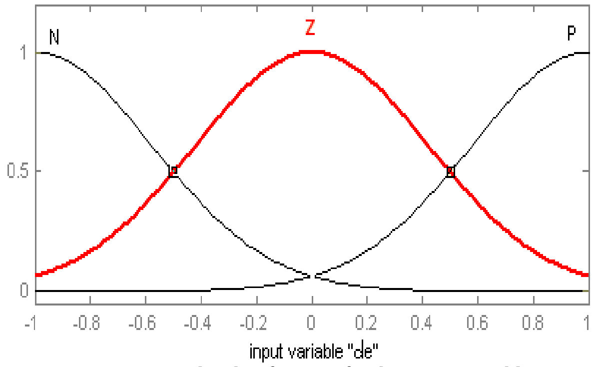


Figure. 4 Membership function for the inputs variables

The fuzzy controller for every phase is characterized for the following:

- Three fuzzy sets for each input,
- Three fuzzy sets for each output,
- Triangular and trapezoidal membership functions,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication.
- Defuzzification using the "centroid" method.

The linguistic rules for the fuzzy current controller are as follows:

1. If error is Negative and error rate is Negative Then output is Big Negative,
2. If error is Zero and error rate is Negative Then output is Positive,
3. If error is Positive and error rate is Negative Then output is Big Positive,
4. If error is Negative and error rate is Negative Then output in Big Negative,
5. If error is Zero and error rate is Zero Then output is Zero,
6. If error is Positive and error rate is Zero Then output is Big Positive,
7. If error is Negative and error rate is Positive Big Then output is Big Negative,
8. If error is Zero and error rate is Positive Then output is Negative,
9. If error is Positive and error rate is Positive Then output is Big Positive.

The generation process of switching signals is given by Fig.5.

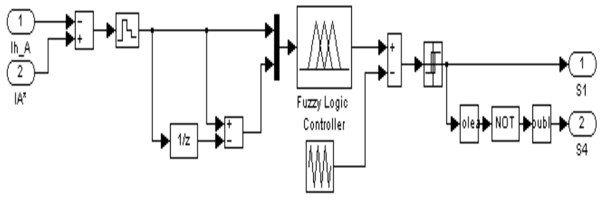


Figure.5 Generation process of switching signals

Fig.6 show the Matlab-Simulink simulation block diagram of the proposed fuzzy current controller based on ANN dc voltage regulator for the three-phase shunt active filter under ideal voltages conditions.

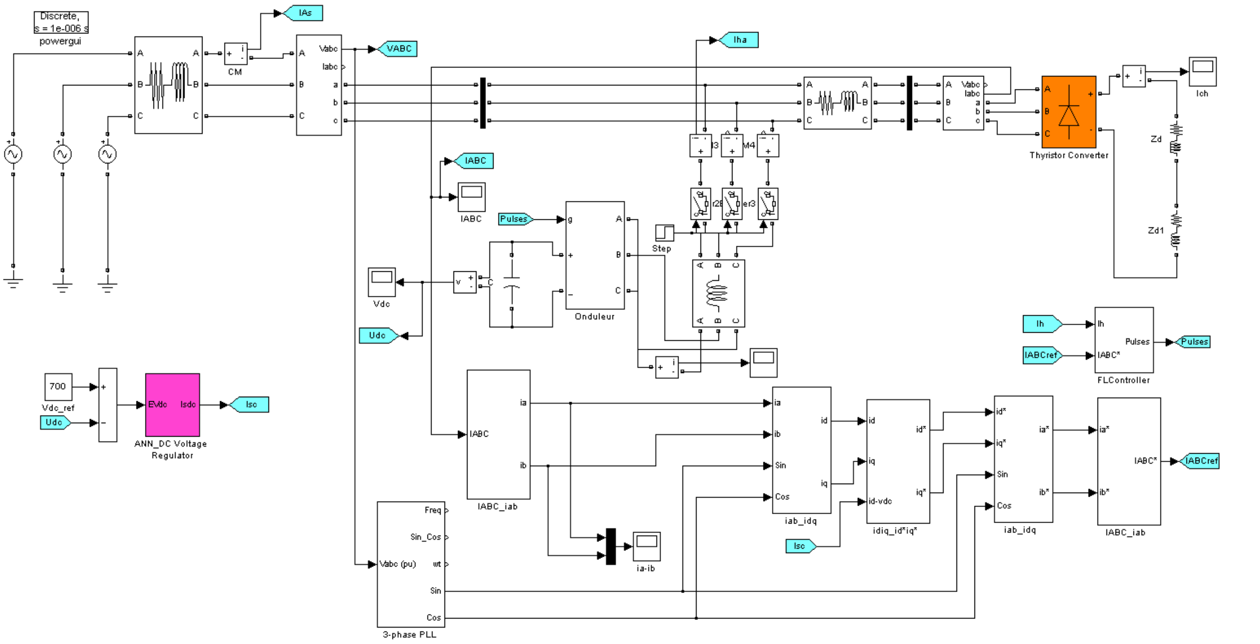


Figure.6 Matlab-Simulink simulation block diagram of the SAF

VI. Simulations

The purpose of the simulation is to show the effectiveness of the shunt active filter using a fuzzy current controller to reducing the harmonic currents produced on the load side under ideal voltages conditions using synchronous reference frame detection method algorithm for references currents identification. The model parameters used for simulation are:
Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_{ch} =48.6Ω, Inductance L_{ch}=40mH, DC Voltage U_{dc} =700V, Capacitance C_{dc}=3000µF, Resistor R_c=0.27m Ω, Inductance L_c=0.8mH.

Fig.7, Fig.8 and Fig.9 shows the voltage source, line current and its spectrum before compensation.

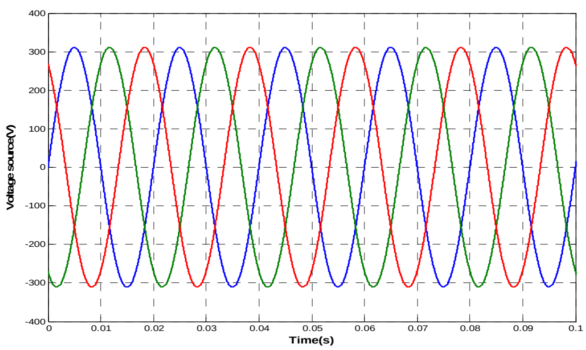


Figure.7 Supply voltage

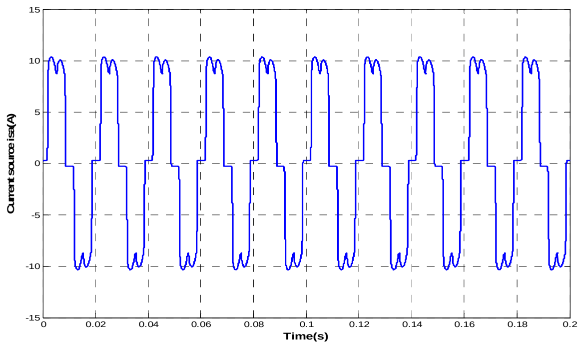


Figure.8 Source current

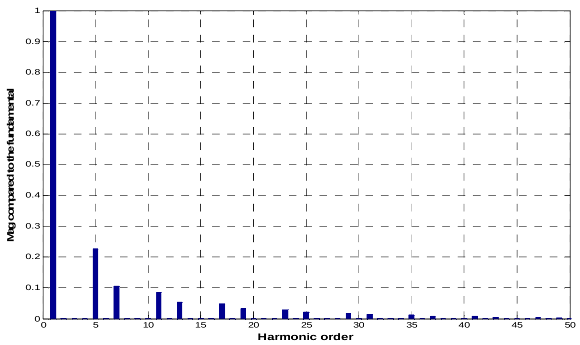


Figure.9 Source current Spectrum THD 28.16%

The line current and its spectrum after compensation are represented in Fig.10 and Fig.11.

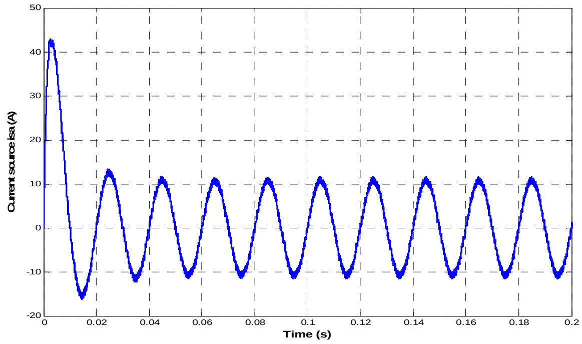


Figure.10 Source current

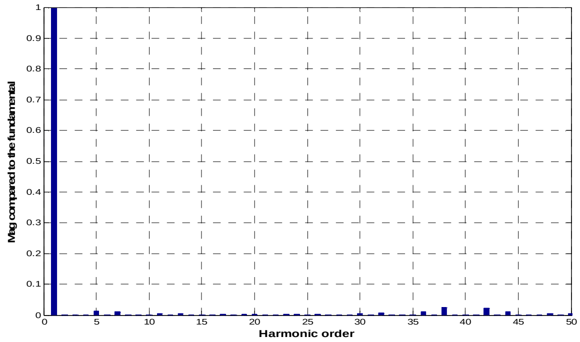


Figure.11 Source current spectrum THD 5.34%

Fig.12 show the current and voltage source, finally the dc voltage is presented in Fig.13.

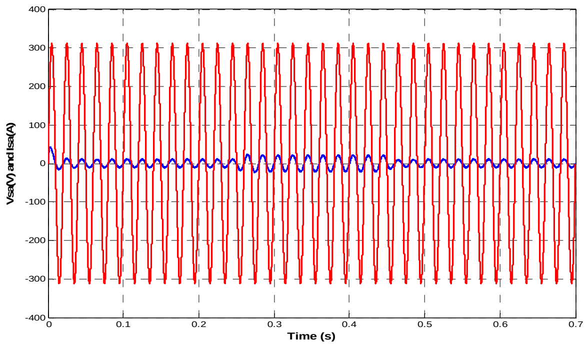


Figure.12 Current and source voltage

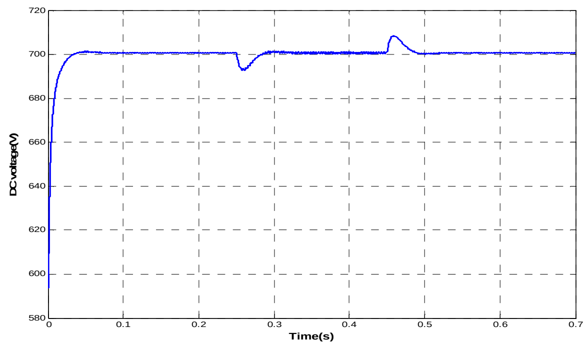


Figure.13 DC voltage capacitor

The simulation results show that the source current becomes closely sinusoidal and the THD is reduced from 28.16% to 5.34% after compensation. The dynamic response of the proposed ANN DC voltage regulator is very good.

VII. CONCLUSION

In this paper, a fuzzy current controller associated to ANN's dc voltage regulator for shunt active filter has been proposed to compensate harmonic currents under ideal voltage conditions. The simulation results prove the effectiveness of the designed active filter based on FLC and ANN controllers. The source current becomes closely sinusoidal and in phase with source. The THD is reduced to 5.34% after compensation in conformity with the standard IEEE recommendations.

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Shunt Active Filter based on Intelligent Controllers to Compensate Harmonic Currents using Two Control Strategies

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***Abstract* — This paper presents a three-phase three-wire shunt active filter based on intelligent controllers to compensate harmonic currents. Shunt active filter is the best solution to eliminate harmonics drawn from nonlinear load especially for low power system, the most inverter used is the two-level voltage source. The control strategies adopted are the synchronous reference frame detection method for the fuzzy logic controller and the synchronous current detection method for the ANN controller. The advantages of the two controllers proposed in this paper that are based on linguistic description, does not require an accurate mathematical model and can work with imprecise inputs. The dc voltage capacitor is controlled by conventional PI regulator to maintain it constant. The numerical simulation results, using MATLAB-Simulink and Power System BlockSet Toolbox, from complete structure including control and power circuits are presented and discussed.**

***Keywords* — Shunt active filter, Intelligent controllers, ANNs, FLC, Harmonic currents compensation.**

I. Introduction

With the proliferation of nonlinear power electronics loads, the problem of harmonic is severity, which influences the power quality of power grid. Passive power filter is a traditional harmonic restraint method. The passive filtering is a simple way to eliminate the harmonic currents. However, it does not allow to completely eliminating all of them and has many drawbacks such as series or parallel resonance with the system impedance [1].

Active filter is used, these last years, to improve power quality on the load side from the grid current, by injecting compensating currents [2]. The performance of an active filter mainly depends on the reference current generation strategy, hysteresis or PWM control, topology of the power converter, etc…

In recent years, fuzzy logic and ANN controllers have generated a great deal of interest in certain applications [3],[4]. The advantages of these controllers are: robustness, no need to accurate mathematical model, can work with imprecise inputs and can handle non-linearity.

In this paper, fuzzy logic and artificial neural network current controllers are proposed to control the three-phase shunt active filter with two different control strategies, the synchronous reference frame detection algorithm and the synchronous current detection method.

The performances of shunt active filter based on these controllers are evaluated using Matlab-Simulink and power system Block Set Toolbox under balanced voltage conditions. The obtained results showed that, the two proposed shunt active filter control scheme produced a sinusoidal supply current with acceptable low harmonic distortion.

II. Shunt Active Filter

The basic block diagram including non linear load compensation principle of a shunt active power filter is shown in Fig.1. It is controlled to draw/supply a compensated current from/to the utility, such that it cancels harmonic currents of the non-linear load and makes the source current in phase with the different waveforms. The current drawn from the power system at the coupling point of the shunt APF will result sinusoidal [5],[6].

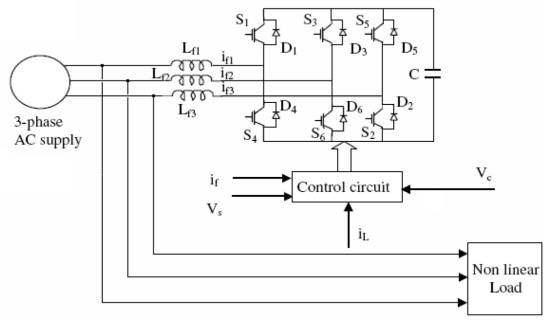

Fig.1 Shunt active filter

III. Control Strategies

A. Synchronous reference frame detection method

The first control strategy used in this work to compensate harmonic currents is based on the synchronous reference frame detection method. The principle of this method is described below [7]. The three phase currents i_a, i_b and i_c are transformed from three phase (abc) reference frame to two phase's $(\alpha-\beta)$ stationary reference frame currents i_α and i_β using:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (1)$$

Using a PLL (Phase Locked Loop), we can generate $\cos(\theta_{est})$ and $\sin(\theta_{est})$ from the phase voltage source v_{sa}, v_{sb}, v_{sc}.

The currents expression i_α and i_β in $(d-q)$ reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2)$$

The DC quantities and all other harmonics are transformed to non DC quantities using a low pass filter:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \qquad (3)$$

The expression of the reference current $i_{\alpha-ref}$ and $i_{\beta-ref}$ are given by:

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \qquad (5)$$

The reference currents in the (abc) frame is given by:

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \qquad (6)$$

Finally, the compensation currents (i_{ca}, i_{cb} and i_{cc}) are given by:

$$\begin{aligned} i_{ca} &= i_{a-ref} - i_{La} \\ i_{cb} &= i_{b-ref} - i_{Lb} \\ i_{cc} &= i_{c-ref} - i_{Lc} \end{aligned} \qquad (7)$$

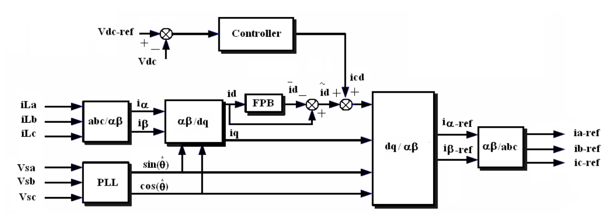

Fig.2 Principle scheme of the synchronous reference frame detection method

B. Synchronous current detection method

The second control strategy is inspired of the synchronous detection reference currents method [3]. It is based on the measuring of the source voltages (v_{sa}, v_{sb}, v_{sc}) given by (8) :

$$\begin{aligned} v_{sa}(t) &= V_{sm}.\sin(\omega t) \\ v_{sb}(t) &= V_{sm}.\sin(\omega t - \frac{2\pi}{3}) \\ v_{sa}(t) &= V_{sm}.\sin(\omega t - \frac{4\pi}{3}) \end{aligned} \qquad (8)$$

The maximum amplitude of the current supplied by the filter I^*_{smax} is given by (9):

$$I^*_{s\max} = I^*_{smp} + I^*_{smd} \qquad (9)$$

With :

$$I^*_{smp} = \frac{2}{3}\frac{P_{moy}}{V_{sm}} \qquad (10)$$

I^*_{smd} is the component current which maintains the DC voltage across the capacitor C_{cd} [7]. The reference currents must be sinusoidal and in phase with the voltage source. The desired current source AC can be calculated by multiplying the maximum amplitude of the current source of sinusoidal signals unit. These unit signals are given by (11):

$$\begin{aligned} i_{ua}(t) &= v_{sa}/V_{sm} \\ i_{ub}(t) &= v_{sb}/V_{sm} \\ i_{uc}(t) &= v_{sc}/V_{sm} \end{aligned} \qquad (11)$$

$$\begin{aligned} i^*_{sa}(t) &= I^*_{sm}.i_{ua} \\ i^*_{sb}(t) &= I^*_{sm}.i_{ub} \\ i^*_{sc}(t) &= I^*_{sm}.i_{uc} \end{aligned} \qquad (12)$$

The difference between the current references and the current drawn by the load can generate the three compensation current (i^*_{ca}, i^*_{cb} et i^*_{cc}) :

$$\begin{aligned} i^*_{ca} &= i^*_{sa} - i_{La} \\ i^*_{cb} &= i^*_{sb} - i_{Lb} \\ i^*_{cc} &= i^*_{sc} - i_{Lc} \end{aligned} \qquad (13)$$

Fig.3 shows the principle scheme of the synchronous current detection method.

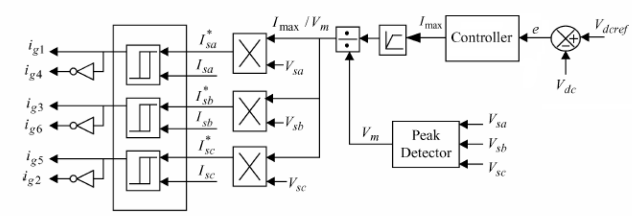

Fig.3 principle scheme of the synchronous current detection method

IV. DC VOLTAGE CONTROLLER

The regulation loop consists of the comparison of the measured voltage with the reference voltage, admitting that the function of the system to be controlled is given by [8]:

$$\frac{V_s^{\,2}}{(V_{dc-ref}.C_{dc}.s)} \tag{14}$$

The closed loop transfer function using a PI regulator is given by:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{(K_p + K_i/s).(V_s^{\,2}/(V_{dc-ref}.C_{dc}.s))}{1+(K_p + K_i/s).(V_s^{\,2}/(V_{dc-ref}.C_{dc}.s))} \tag{15}$$

The development of this equation gives:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{\dfrac{K_p V_s^{\,2}}{V_{dc-ref}.C_{dc}}.s + \dfrac{K_i}{V_{dc-ref}.C_{dc}}}{s^2 + \dfrac{K_p V_s^{\,2}}{V_{dc-ref}.C_{dc}}.s + \dfrac{K_i V_s^{\,2}}{V_{dc-ref}.C_{dc}}} \tag{16}$$

A second order characteristic equation of the closed loop system is deduced:

$$s^2 + 2\xi\omega_n s + \omega_n^{\,2} = 0 \tag{17}$$

Where:

$$\omega_n = \sqrt{\frac{K_i V_s^{\,2}}{V_{dc-ref}.C_{dc}}} \;,\; \xi = \frac{K_p V_s}{2\sqrt{K_i V_{dc-ref}.C_{dc}}} \tag{18}$$

From (11) the proportional and integrator coefficient K_p , K_i of the controller can be deduced:

$$K_p = \frac{2.\xi.K_i}{\omega_n} \;,\; K_i = \frac{\omega_n^{\,2} V_{dc-ref}.C_{dc}}{V_s^{\,2}} \tag{19}$$

The expression of the current I_{sc} to compensate the inverter losses and maintain the constant dc-link voltage is given by:

$$I_{sc} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \tag{20}$$

To obtain optimal dynamic performance for the system, the value of the damping ration ξ must be equal a 0.707.

V. ARTIFICIAL INTELLIGENT CONTROLLERS

A. Fuzzy logic current controller

The main component of an active filter is the current controller. Generally the classical hysteresis controller is used to generate pulses to the PWM inverter; it is very stable and generates a minimum noise.

Recently, fuzzy logic controllers (FLCs) have been interest a good alternative in more application. The advantage of fuzzy systems are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, and they are more robust than conventional nonlinear controllers [9],[10].

Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. To develop the rules of the fuzzy logic, we need good understand of the process to be controlled, but it does not require a complicated mathematical model. The desired switching signals for the filter inverter circuit are determined according to the error in the filter current. In this case, the fuzzy logic current controller has two inputs, named error *e* and change of error *de* and one output named *s*. Here the error *e* and change of error *de* are the input variable for the system. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig. 4 shows the membership functions used in fuzzification.

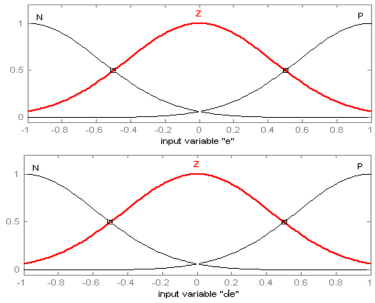

Fig.4 Membership function for the inputs variables

The fuzzy controller for every phase is characterized for the following:

- Three fuzzy sets for each input,
- Three fuzzy sets for each output,
- Triangular and trapezoidal membership functions,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication.
- Defuzzification using the "centroid" method.

The linguistic rules for the fuzzy current controller are as follows:

1. If error is Negative and error rate is Negative Then output is Big Negative,
2. If error is Zero and error rate is Negative Then output is Positive,
3. If error is Positive and error rate is Negative Then output is Big Positive,
4. If error is Negative and error rate is Negative Then output in Big Negative,
5. If error is Zero and error rate is Zero Then output is Zero,
6. If error is Positive and error rate is Zero Then output is Big Positive,
7. If error is Negative and error rate is Positive Big Then output is Big Negative,
8. If error is Zero and error rate is Positive Then output is Negative,
9. If error is Positive and error rate is Positive Then output is Big Positive.

The generation process of switching signals is given by Fig.5.

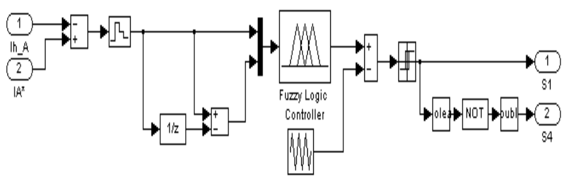

Fig.5 Generation process of switching signals

Fig.6 shows the Matlab-Simulink simulation block diagram of the proposed fuzzy current controller for the three-phase shunt active filter.

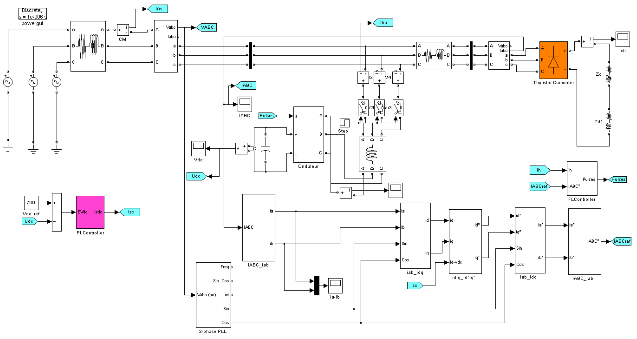

Fig.6 Shunt active filter based on Fuzzy current controller

B. Artificial neural network current controller

Artificial Neural Networks have provided an alternative modeling approach for power system applications. The MLPN is one of the most popular topologies in use today. This network consists of a set of input neurons, output neurons and one or more hidden layers of intermediate neurons. Data flows into the network through the input layer, passes through the hidden layers and finally flows out of the network through the output layer. The network thus has a simple interpretation as a form of input-output model, with network weights as free parameters. The use and training of MLPNs is well understood [11].

The objective of the training is to modify weight matrices W and V such that the ANN function approximates the plant function and the error e between the desired function output y and the ANN output $\hat{y}$ is minimal. The training cycle has two distinct paths:

- Forward propagation: It is the passing of inputs through the neural network structure to its output.
- Error back-propagation: It is the passing of the output error to the input in order to estimate the individual contribution of each weight in the network to the final output error. The weights are then modified so as to reduce the output error.

The input pattern of the current controller network is the error values (Ei_a, Ei_b, Ei_c) between the measured filter currents (i_{ha}, i_{hb}, i_{hc}) and the compensating reference currents $(i^*_{ca}, i^*_{cb}, i^*_{cc})$ whereas the outputs values are the switching states Sa, Sb, Sc for every phase. The hidden layer contains 20 neurons with a sigmoid activation function, whereas the output layer contains three neurons with a linear activation function. The network was trained using Levenberg-Marquardt back propagation algorithm, about 10000 training examples obtained by simulation.

Fig.7 shows the Matlab-Simulink simulation block diagram of the proposed ANN controller for the three-phase shunt active filter.

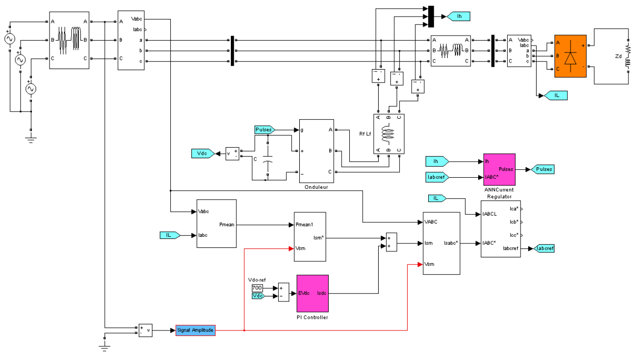

Fig.7 Shunt active filter using ANN current controller

VI. SIMULATIONS

The purpose of the simulation is to show the effectiveness of the shunt active filter using intelligent controllers (fuzzy logic and ANN current controllers) to reducing the harmonic currents produced on the load side under ideal voltages conditions. The model parameters used for simulation are:

Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_{ch} =48.6Ω, Inductance L_{ch}=40mH, DC Voltage U_{dc} =700V, Capacitance C_{dc}=3000μF, Resistor R_c=0.27m Ω, Inductance L_c=0.8mH.

Fig.8 shows the voltage source, line current and its spectrum before compensation

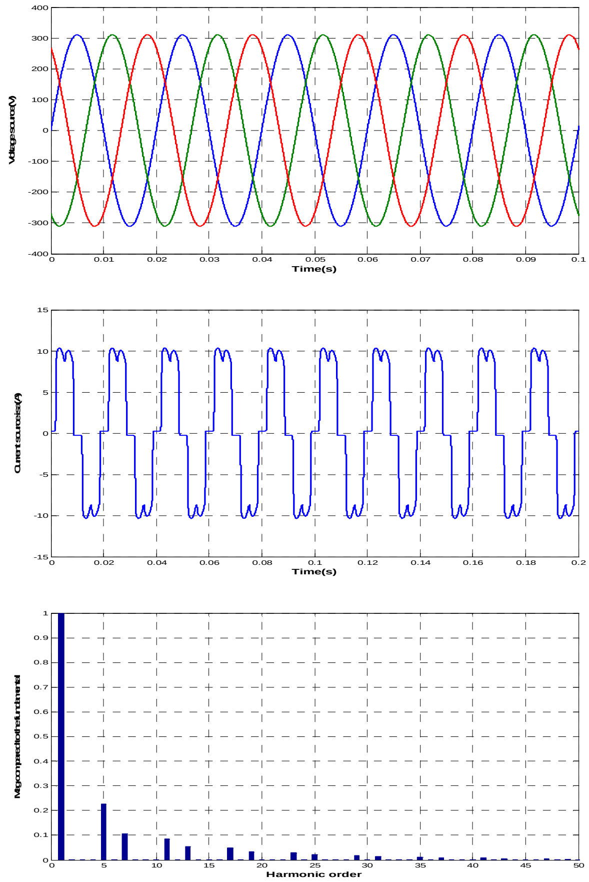

Fig.8 Voltage source, line current and its spectrum before compensation

The line current and its spectrum after compensation using fuzzy logic controller are represented in Fig.9 and Fig.10.

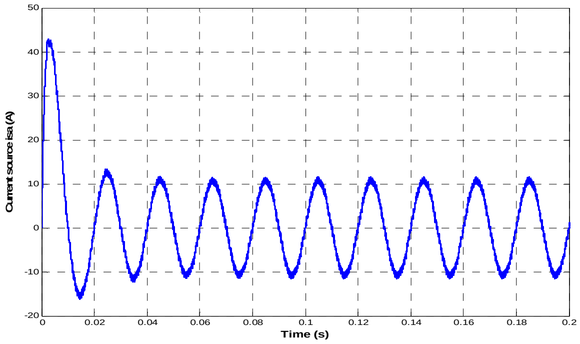

Fig.9 Source current (FLC)

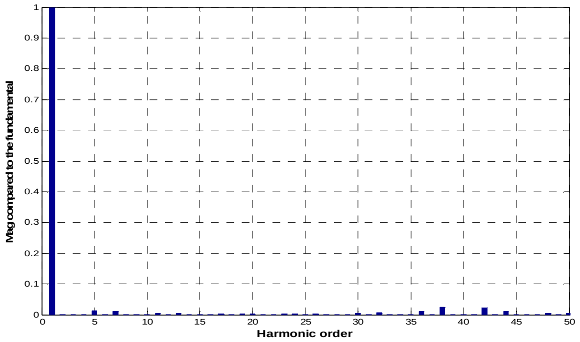

Fig10 Source current spectrum THD 2.28% (FLC)

Fig.11 shows that the current and voltage source after compensation are in phase.

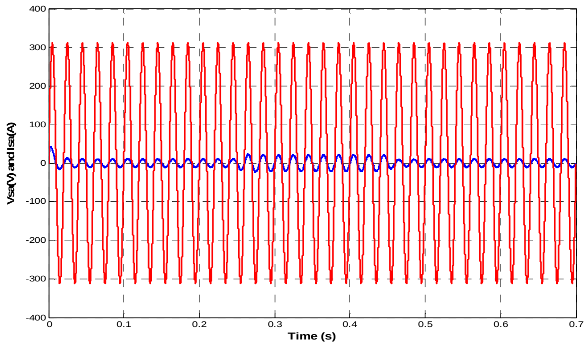

Fig.11 Current and source voltage (FLC)

The line current and its spectrum after compensation using artificial neural network current controller are represented in Fig.12 and Fig.13

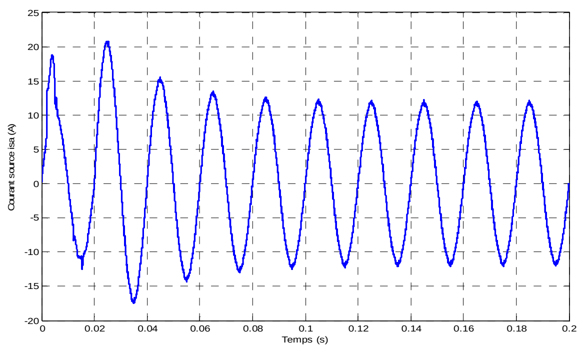

Fig.12 Source current (ANN)

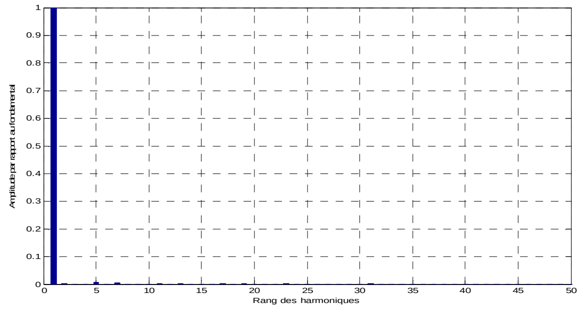

Fig13 Source current spectrum THD 1.49% (ANN)

The simulation results show that the source current becomes closely sinusoidal for the two controllers, the THD is respectively reduced from 28.16% to 2.28% (FLC) and 1.49% (ANN) after compensation.

VII. CONCLUSION

In this paper, a fuzzy and artificial neural network current controller for shunt active filter has been proposed to compensate harmonic currents under ideal voltage conditions. The simulation results prove the effectiveness of the designed active filter based on these intelligent controllers. The source current becomes closely sinusoidal and in phase with source after compensation in conformity with the standard IEEE recommendations.

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Improved Power Energy Quality using a Shunt Active Filter based on Fuzzy Control operating under Non Ideal Voltage Conditions

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***Abstract*—This paper presents a three-phase three-wire shunt active filter based on a fuzzy current controller to compensate harmonic current perturbations under non ideal voltage conditions. The control strategy which is adopted uses synchronous reference frame detection method; it is generally used if the source voltage is unbalanced or distorted. Today, fuzzy logic controllers are used in various power electronics applications; their advantages are simple design, no need of mathematical model, based on linguistic description and are more robust than conventional controllers. To compensate the inverter losses and maintain the dc voltage capacitor constant a proportional integral controller is used. The simulation model is developed and performed using MATLAB-Simulink and SimPowerSystem Toolbox. The simulation results obtained show the effectiveness of the proposed Shunt Active Filter (SAF) system under non ideal voltage conditions.**

Keywords- ***Shunt active power filter, Fuzzy current controller, Synchronous reference detection method, Harmonic currents compensation, Non ideal voltages conditions.***

I. INTRODUCTION

A large part of total electrical energy, produced in the world, supplies different types of non-linear loads. The loads such as variable frequency drives and electronic ballasts draw current, which does not resemble the grid sinusoidal voltage. This load is said to be non-linear and typically is composed of odd order currents, which are expressed as multiples of the fundamental frequency. The harmonic current cannot contribute to active power and needs to be eliminated to enhance the power quality [1]. Active Power Filter (APF) is the popular solution used to eliminate the undesired current components by injection of compensation currents in opposition to them [2],[3].

The performance of any active filter mainly depends on the reference current generation strategy, control techniques, converter topology, etc…

Several papers studied and compared the performances of different reference current generation strategies under balanced, sinusoidal, unbalanced or distorted voltage conditions [3],[4]. In all of them, the p-q strategy and SRF provide similar performances. But when, the active filter work under distorted and unbalanced AC voltages (real conditions) the best results are obtained with the synchronous reference frame method. However, the SRF theory requires a phase locked loop (PLL) which increases the complexity of the control system.

In recent years, fuzzy logic controllers have generated a great deal of interest in different applications [5,6]. Their advantages are robustness, no need mathematical model and accept non-linearity. This paper is focused on the compensation current harmonic capability using three-phase shunt active filter based on fuzzy logic current controller under non ideal voltages conditions.

The performances of the proposed shunt active filter are evaluated through computer simulations for transient and steady-state conditions using Matlab-Simulink and SimPower System Block-Set Toolbox. The obtained results show the effectiveness and the robustness of the proposed SAPF system under different voltage conditions.

II. SHUNT ACTIVE POWER FILTER

The basic block diagram including non linear load compensation principle of a shunt active power filter is shown in Fig. 1. It is controlled to compensate harmonic currents generated by the non-linear load and makes the source current in phase with the source voltage. After compensation the source current at the coupling point of the shunt APF is sinusoidal and without harmonics [7,8].

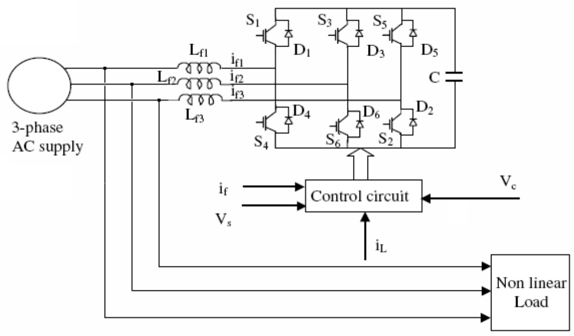


Figure 1. Shunt active filter

III. SYNCHROUNOUS REFERENCE FRAME STRATEGY

The control strategy to compensate harmonic currents used in this work is based on the synchronous reference frame detection method. The principle of this technique is described below [9]. The three phase currents ia, ib and ic are transformed from three phase (abc) reference frame to two phase's (α-β) stationary reference frame currents iα and iβ using:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

Using a PLL (Phase Locked Loop), we can generate cos(θest) and sin(θest) from the phase voltage source vsa, vsb and vsc.

The currents expression iα and iβ in (d-q) reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

The DC quantities and all other harmonics are transformed to non DC quantities using a low pass filter:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \quad (3)$$

The expression of the reference current iα-ref and iβ-ref are given by:

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \quad (5)$$

The reference currents in the (abc) frame are given by:

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \quad (6)$$

Finally, the compensation currents ica, icb and icc are given by:

$$\begin{aligned} i_{ca} &= i_{a-ref} - i_{La} \\ i_{cb} &= i_{b-ref} - i_{Lb} \\ i_{cc} &= i_{c-ref} - i_{Lc} \end{aligned} \quad (7)$$

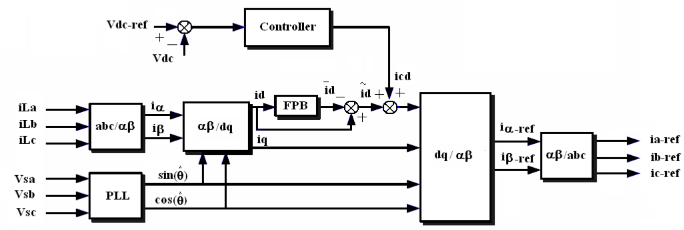


Figure 2. Synchronous reference frame detection method

IV. DC VOLTAGE CONTROLLER

The regulation loop consists of the comparison of the measured voltage with the reference voltage, admitting that the function of the system to be controlled is given by [10],[11]:

$$\frac{V_s^2}{(V_{dc-ref}.C_{dc}.s)} \quad (8)$$

The closed loop transfer function using a PI regulator is given by:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{(K_p + K_i/s).(V_s^2/(V_{dc-ref}.C_{dc}.s))}{1+(K_p + K_i/s).(V_s^2/(V_{dc-ref}.C_{dc}.s))} \quad (9)$$

The development of this equation gives:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{\frac{K_p.V_s^2}{V_{dc-ref}.C_{dc}}.s + \frac{K_i.V_s^2}{V_{dc-ref}.C_{dc}}}{s^2 + \frac{K_p.V_s^2}{V_{dc-ref}.C_{dc}}.s + \frac{K_i.V_s^2}{V_{dc-ref}.C_{dc}}} \quad (10)$$

A second order characteristic equation of the closed loop system is deduced:

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0 \quad (11)$$

Where:

$$\omega_n = \sqrt{\frac{K_i.V_s^2}{V_{dc-ref}.C_{dc}}}, \ \xi = \frac{K_p.V_s}{2\sqrt{K_i.V_{dc-ref}.C_{dc}}} \quad (12)$$

From (11) the proportional and integrator coefficient K_p, K_i of the controller can be deduced:

$$K_p = \frac{2.\xi.K_i}{\omega_n}, \ K_i = \frac{\omega_n^2.V_{dc-ref}.C_{dc}}{V_s^2} \quad (13)$$

The expression of the current I_{sc} to compensate the inverter losses and maintain the constant dc-link voltage is given by:

$$I_{sc} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \quad (14)$$

To obtain optimal dynamic performance for the system, the value of the damping ration ξ must be equal a 0.707.

V. FUZZY LOGIC CONTROLLER

Among the various current control techniques, hysteresis current control is the most extensively used technique. It is easy to realize with high accuracy and fast response. In the hysteresis control technique the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteretic controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. The proposed fuzzy logic current controller provides fixed switching frequency and lower ripple content.

The advantages of fuzzy controllers are more robust than conventional controllers, no need an accurate mathematical model and essentially can accept non-linearity [10],[11].

Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. The desired inverter switching signals of the shunt active filter are determined according the error between the compensate currents and reference currents. A fuzzy controller is designed to improve compensation capability of APF by adjusting the current error using a fuzzy rule. In this case, the fuzzy logic current controller has two inputs, named error e and change of error de and one output named s. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig. 3 shows the membership functions used in fuzzification [12].

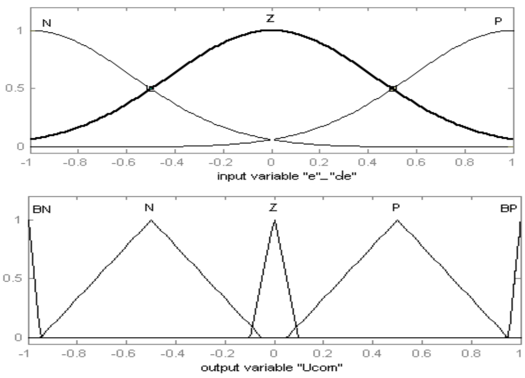


Figure 3. Membership function for the inputs variables

The fuzzy controller for every phase is characterized for the following:

- Three fuzzy sets for each input,
- Five fuzzy sets for each output,
- Triangular and trapezoidal membership functions,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.

The linguistic rules for the fuzzy current controller are as follows:

- If error is Negative and error rate is Negative Then output is Big Negative,
- If error is Zero and error rate is Negative Then output is Positive,
- If error is Positive and error rate is Negative Then output is Big Positive,
- If error is Negative and error rate is Negative Then output in Big Negative,
- If error is Zero and error rate is Zero Then output is Zero,
- If error is Positive and error rate is Zero Then output is Big Positive,
- If error is Negative and error rate is Positive Big Then output is Big Negative,
- If error is Zero and error rate is Positive Then output is Negative,
- If error is Positive and error rate is Positive Then output is Big Positive.

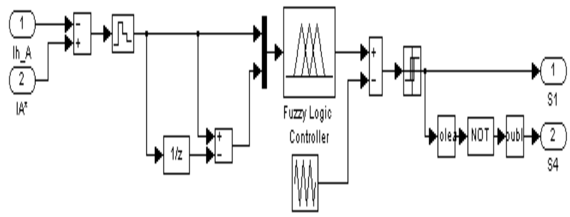


Figure 4. Fuzzy logic inverter switching signals

VI. SIMULATION MOEL

Fig. 5. shows the block diagram of the shunt active filter based on fuzzy current controller developed using Matlab-Simulink and SimPowerSystem Toolbox.

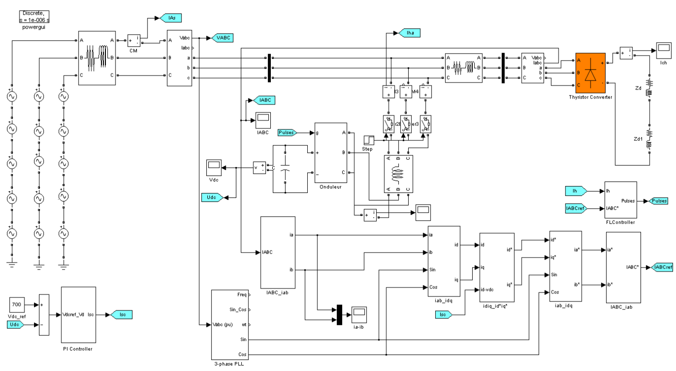


Figure 5. Matlab-Simulink block diagram of the SAF based on Fuzzy controller

VII. SIMULATION RESULTS AND DISSCUSSION

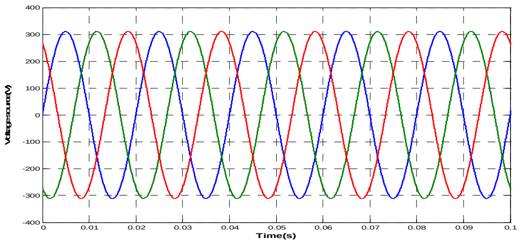
The purpose of the simulation is to show the performances of the shunt active filter operation using a fuzzy current controller to reducing the harmonic currents produced on the load side under non ideal voltages conditions.

The model parameters used for simulation are:

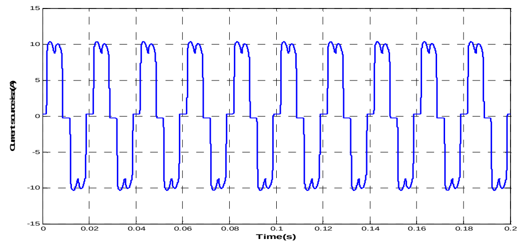
Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_{ch} =48.6Ω, Inductance L_{ch}=40mH, DC Voltage U_{dc} =700V, Capacitance C_{dc}=3000μF, Resistor R_c=0.27m Ω, Inductance L_c=0.8mH.

A. *Ideal voltage conditions case*

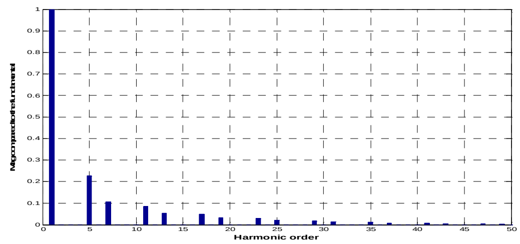
The three-phase voltages source are balanced and do not contain harmonic components, Fig. 6 (a), Fig. 6(b) and Fig. 6 (c) shows the voltage source, line current and its spectrum before compensation. The line current and its spectrum after compensation are presented in Fig. 6 (d) and Fig. 6 (e). Fig. 6 (f) show the current and voltage source, finally Fig. 6 (g) shows the dc voltage.



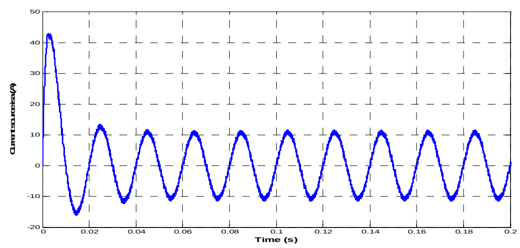
a-Supply voltage



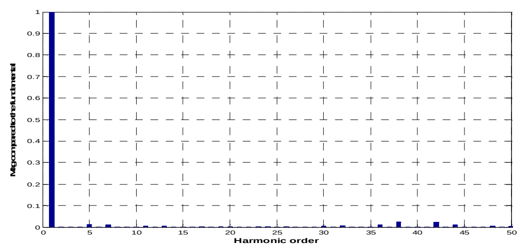
b-Source current before compensation



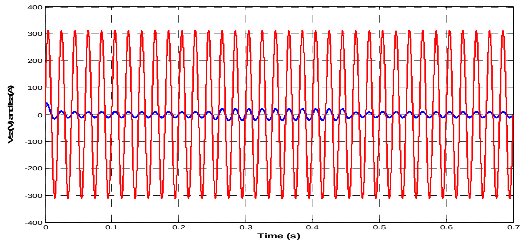
c-Source current Spectrum THD 28.16%



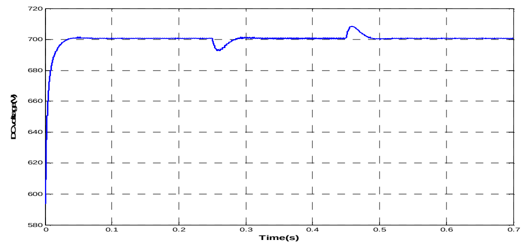
d-Source current after compensation



e-Source current spectrum THD 4.57%



f-Current and source voltage



g-DC voltage capacitor

Figure 6. Ideal voltages conditions

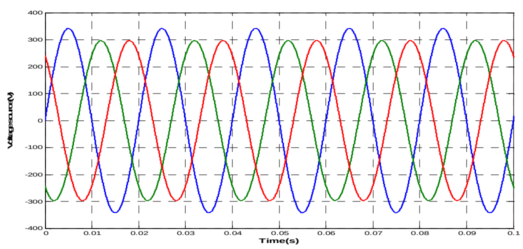
The simulation results show that the source current becomes closely sinusoidal and in phase with the source voltage. The THD is widely reduced from 28.16% to 4.57% after compensation.

B. *Unbalanced voltage conditions case*

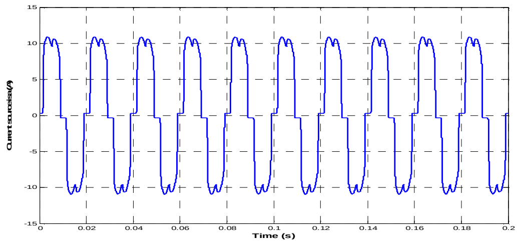
The three phase voltages sources are unbalanced and do not contain harmonic components; their expressions are given by (15):

$$\begin{aligned} v_{sa} &= 311\sin(\omega t) + 31\sin(\omega t) \\ v_{sb} &= 311\sin(\omega t - \frac{2\pi}{3}) + 31\sin(\omega t + \frac{2\pi}{3}) \\ v_{sc} &= 311\sin(\omega t + \frac{2\pi}{3}) + 31\sin(\omega t - \frac{2\pi}{3}) \end{aligned} \quad (15)$$

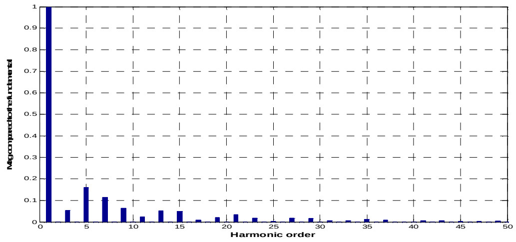
Fig. 7 (a), Fig. 7 (b) and Fig.7 (c) shows the unbalanced voltage source, line current and its spectrum before compensation. The line current and its spectrum after compensation are presented in Fig. 7 (d) and Fig. 7 (e). Fig. 7 (f) show the current and voltage source, finally the dc voltage is presented in Fig. 7 (g).



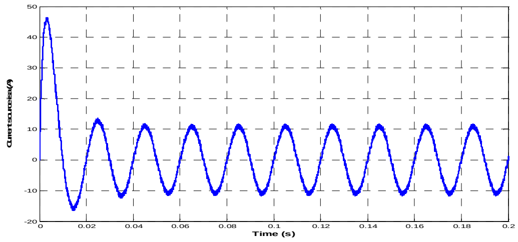
a-Unbalanced voltage



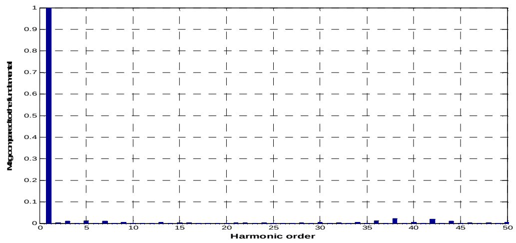
b-Source current before compensation



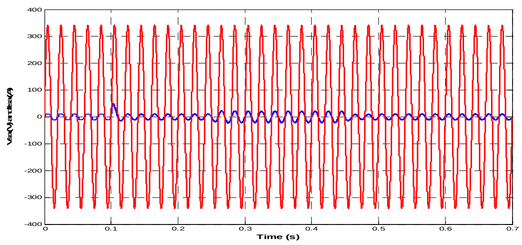
c-Source current Spectrum THD 27.50%



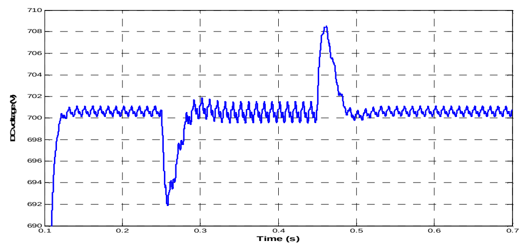
d-Source current after compensation



e-Source current Spectrum THD 4.96%



f-Current and source voltage



g-DC voltage capacitor

Figure 7. Unbalanced voltages conditions

In this case, the line current THD before compensation is 27.50% which is reduced to 4.96% after compensation. The ripples on DC voltage are more than the balanced voltage case.

C. Balanced-distorted voltage conditions case

When the three phase voltages are balanced and distorted, mains voltages contain harmonic voltage components except fundamental component. The expression of the balanced-distorted voltages source used in this work contains the 5th harmonic component and also the 3^{rd,} 7th, 11th harmonic component. For this case, the balanced distorted three phase mains voltages are expressed as below:

$$v_{sa} = 311\sin(\omega t) + 3.7\sin(3\omega t) + 18.6\sin(5\omega t + \frac{4\pi}{3})$$

$$+4.5\sin(7\omega t) + 3.1\sin(11\omega t + \frac{4\pi}{3})$$

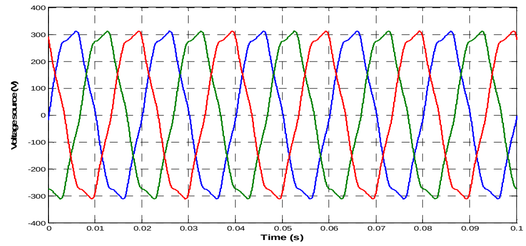
$$v_{sb} = 311\sin(\omega t + \frac{4\pi}{3}) + 3.7\sin(3\omega t) + 18.6\sin(5\omega t)$$

$$+4.5\sin(7\omega t + \frac{4\pi}{3}) + 3.1\sin(11\omega t)$$

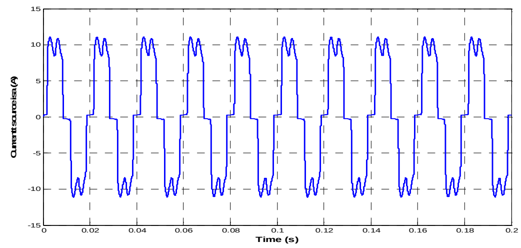
$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 3.7\sin(3\omega t) + 18.6\sin(5\omega t + \frac{2\pi}{3})$$

$$+4.5\sin(7\omega t + \frac{2\pi}{3}) + 3.1\sin(11\omega t + \frac{2\pi}{3})$$

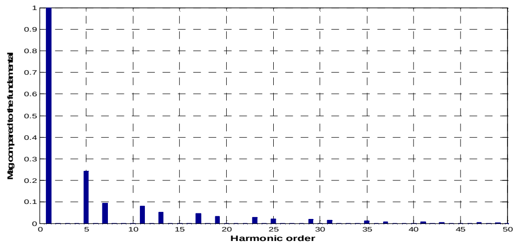
Fig. 8(a), Fig. 8(b) and Fig. 8(c) shows the balanced-distorted voltage source, line current and its spectrum before compensation. The line current and its spectrum after compensation are presented in Fig. 8(d) and Fig. 8(e). Fig. 8(f) show the current and the voltage source, finally the dc voltage is presented in Fig. 8 (g).



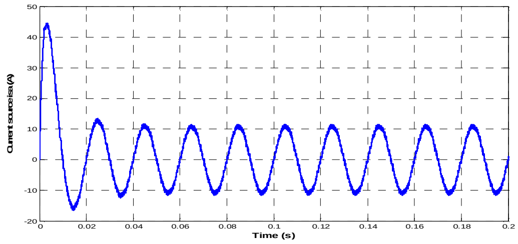
a-Balanced-distorted voltage



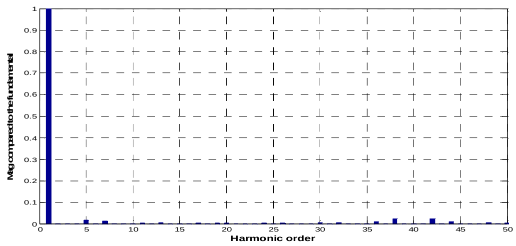
b-Current source before compensation



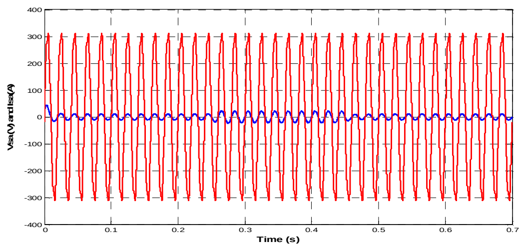
c-Source current Spectrum THD 28.75%



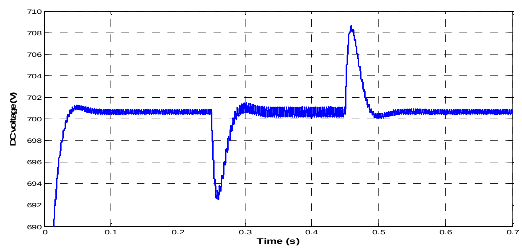
d-Source current after compensation



e-Source current Spectrum THD 4.74%



f-Current and source voltage



g-DC voltage capacitor
Figure 8. Balanced and distorted voltages source

By inspecting Fig. 6(b), Fig. 7(b), Fig. 8(b) of the source current after compensation in all cases, we can see obviously the success in simulating of the harmonic currents compensation using fuzzy logic current controller. The current source is sinusoidal and in phase with voltage source, the power factor is nearly equal to unity. The THD values obtained in different cases with the proposed controller respect the IEEE standard Norms. The DC voltage capacitor is maintained constant and equal to U_{dc-ref}=700V using a proportional integral controller. The dynamic response is very fast in case of step change in load current. Fig. 6(g), Fig. 7(g), Fig. 8(g) shows that the ripples on DC voltage are more important in unbalanced voltage case than the balanced-distorted voltage case. The minimum of the ripple are obtained in the balanced voltage case.

VIII. CONCLUSION

To improve the power quality and to reduce the current source harmonics, a shunt active power filter configuration using fuzzy logic current controller operating under non ideal voltage conditions has been proposed in this paper.

The simulation is performed using MATLAB-Simulink and SimPowerSystem Toolbox. The simulations results show the efficiency of the proposed controller in different cases of source voltage. For all cases, the source current after compensation is sinusoidal and in phase with line voltage source. The current harmonic spectrum respects IEEE standard Norms.

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Three-phase Series Active Power Filter to Protect Sensible Loads based on Fuzzy Voltage Controller at Distorted Supply Network

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***Abstract*—This paper presents a three-phase three-wire series active power filter to compensate voltage harmonics perturbation for specific and sensible loads at distorted supply network. The conventional configuration is based on two-level voltage source inverter with hysteresis controller requiring a complex and a complicated mathematical model. To overcome this drawback and improve the series APF capability, a new control scheme using fuzzy control techniques is adopted in this work. Today fuzzy logic controllers are successfully employed in various industrial applications; their advantages are robustness and easy implementation. The proposed fuzzy voltage controller is designed to improve compensation capability of series active power filter by adjusting the voltage error using a fuzzy rule. The control strategy use instantaneous reactive power theory easy to implement and gives an excellent performances. The simulation is performed using MATLAB-Simulink and SimPowerSystem BlockSet Toolbox. The simulation results from complete structure including control and power circuits are presented and discussed.**

Keywords-Series active power filter, Fuzzy logic voltage controller, Distorted supply network, Voltage harmonics, Sensible loads.

I. INTRODUCTION

With the continuous proliferation of non linear loads, harmonic pollution is being considered as one of the major problems that degrade the power quality. So far, active power filters have been proposed as an interesting and high performance solution to improve the power quality [1]. Shunt active power filter is generally used to compensate current harmonics. Series active power filter are used to compensate different types of voltage perturbations, such as voltage unbalances, sags, harmonics and voltage swells, these perturbations have harmful effects on the electric equipments [2].

The usual configuration of series active filters is based on PWM-VSI; it is inserted in series between the load and the source voltage. Three single phase transformers are used to perform the series connection. The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [3,4], to improve the Series APF performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic controllers. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. The fuzzy control does not need an accurate mathematical model of a plant. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. Thus, control design is simple since it is only based on if....then linguistic rules [5,6,7].

The investigation in this paper concentrates on the fuzzy control approaches for the three-phase series APF for compensating especially voltage harmonics perturbation. The control strategy used is the instantaneous reactive power theory [8].

The performance of series active filter based on fuzzy voltage controller under voltage harmonics perturbation is evaluated using Matlab-Simulink and SimPowerSystem Block-Set Toolbox. The obtained results show the effectiveness of the proposed control scheme.

II. SERIES ACTIVE POWER FILTER

The circuit configuration of the series active filter is shown in Fig. 1, the Series AF is inserted between the perturbed voltage source and a protected load. It is composed of three phase voltage source converter, L_fC_f filter to suppress switching ripples and series transformers which inject the compensating voltage to the line [9].

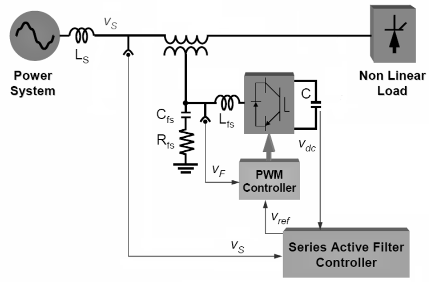


Figure 1. Series active power filter

III. HARMONIC VOLTAGE IDENTIFICATION

The proposed series active filter is adopted to compensate particularly voltage harmonics. The control strategy used for extracting the reference voltages of series active power filter is based on the p-q theory described in [10,11].

We assume that the three-phase voltage source in the grid is symmetric and distorted:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t - \frac{2\pi}{3}) + \theta_n \right] \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t + \frac{2\pi}{3}) + \theta_n \right] \end{bmatrix} \quad (1)$$

Un and θn are respectively the rms voltage and initial phase angle, n is the harmonic order.

When n=1, it means three-phase fundamental voltage source:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sqrt{2} U_1 \sin(\omega t + \theta_1) \\ \sqrt{2} U_1 \sin\left[(\omega t - \frac{2\pi}{3}) + \theta_1 \right] \\ \sqrt{2} U_1 \sin\left[(\omega t + \frac{2\pi}{3}) + \theta_1 \right] \end{bmatrix} \quad (2)$$

Equation (1) is transformed into (α–β) reference frame:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = C_{32} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \sqrt{3} \begin{bmatrix} \sum_{n=1}^{\infty} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \mp U_n \sin(n\omega t + \theta_n) \end{bmatrix} \quad (3)$$

Where:

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (4)$$

Three-phase positive fundamental current template is constructed:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (5)$$

Equation (5) is transformed to (α–β) reference frame:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t \end{bmatrix} \quad (6)$$

According to the instantaneous reactive power theory [11], then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

Where DC and AC components are included:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \quad (8)$$

P and q are passed through low pass filter (LPF) and DC component are got:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \sqrt{3} \begin{bmatrix} U_1 \cos(\theta_1) \\ U_1 \sin(\theta_1) \end{bmatrix} \quad (9)$$

According to (7), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \quad (10)$$

As for DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} u_{\alpha f} & u_{\beta f} \\ u_{\beta f} & -u_{\alpha f} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} \quad (11)$$

The fundamental voltages in (α–β) reference frame are:

$$\begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (12)$$

The three-phase fundamental voltage is:

$$\begin{bmatrix} U_{af} \\ U_{bf} \\ U_{cf} \end{bmatrix} = C_{23} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \sqrt{2} U_1 \begin{bmatrix} \sin(\omega t + \theta_1) \\ \sin(\omega t + \theta_1 - \frac{2\pi}{3}) \\ \sin(\omega t + \theta_1 + \frac{2\pi}{3}) \end{bmatrix} \quad (13)$$

Where:

$$C\,23 = \begin{bmatrix} 1 & 0 \\ -1/2 & \frac{\sqrt{3}}{2} \\ -1/2 & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (14)$$

Finally, the block diagram of this algorithm is presented in Fig.2.

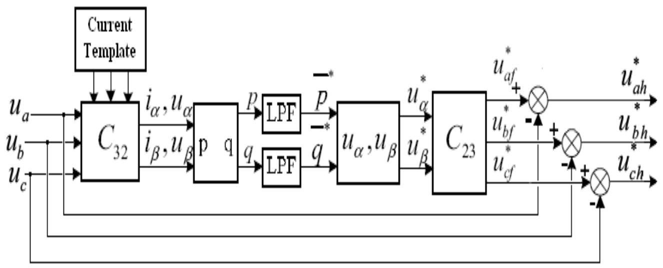


Figure 2. Block diagram of voltages reference identification

IV. FUZZY LOGIC VOLTAGE CONTROLLER

Fuzzy logic controllers (FLCs) have been interest a good alternative in more power electronics application. Their advantages are robustness, not need a mathematical model and accepting non-linearity [12,13]. To benefit of these advantages new simple fuzzy logic voltage controller for three-level inverter is designed. Fuzzy logic unlike Boolean or crisp logic, deal with problems that have vagueness, uncertainty or imprecision and uses membership functions with values varying between 0 and 1. Fig. 3 shows a schematic block diagram of fuzzy inference system or fuzzy controller [14].

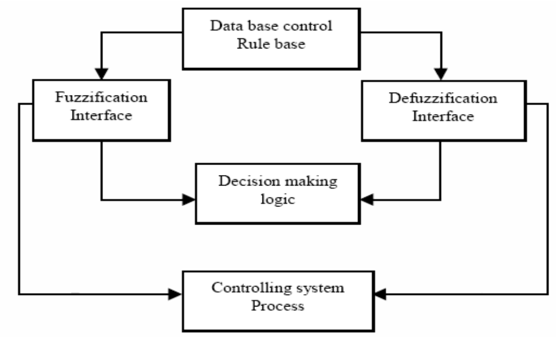
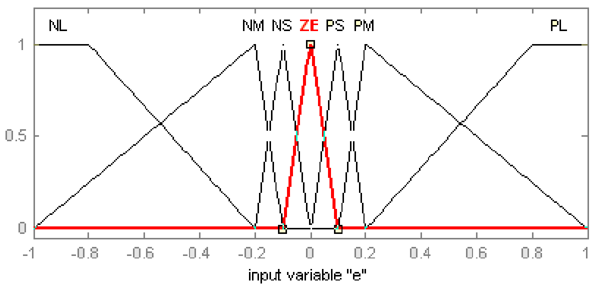


Figure 3. Fuzzy inference system

The fuzzy voltage controller proposed in this paper is designed to improve compensation capability of APF by adjusting the voltage error using fuzzy rules. The desired inverter switching signals are determined according the error between the compensate voltages and reference voltages. In this case, the fuzzy logic voltage controller has two inputs, error e and change of error de and one output s. To convert it into linguistic variable, we use seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large). The membership functions used in fuzzification and defuzzification are shown in Fig. 4.

The fuzzy controller for every phase is characterized for the following:

- Seven fuzzy sets for each input,
- Seven fuzzy sets for output,
- Triangular and trapezoidal membership function for the inputs and output,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.



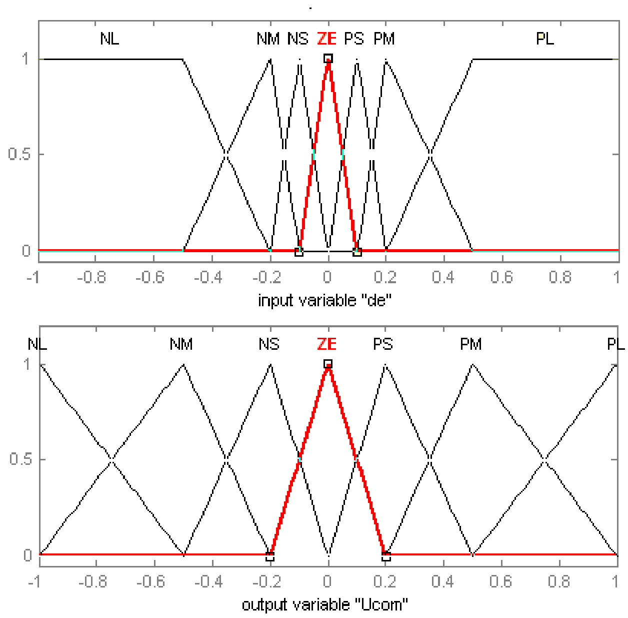


Figure 4. Membership function for the inputs and output variables

The fuzzy rules are given by Table (1).

e de/dt	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	EZ
NM	NL	NM	NM	NS	NS	EZ	PS
NS	NM	NM	NS	NS	EZ	PS	PS
ZE	NM	NS	NS	EZ	PS	PS	PM
PS	NS	NS	EZ	PS	PS	PM	PM
PM	NS	EZ	PS	PS	PM	PM	PL
PL	EZ	PS	PS	PM	PM	PL	PL

Table (1) Fuzzy rules

The generation process of switching signals is given by Fig.5.

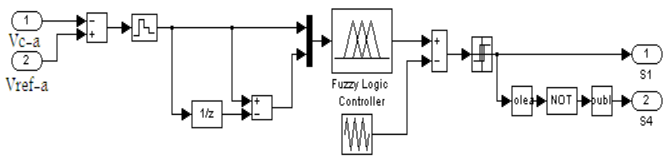


Figure 5. Switching signals generation based on fuzzy controller

The controller calculates the difference between the injected voltage and the reference voltage that determines the reference voltage of the inverter. This fuzzy voltage is compared with carrying triangular waves and generates switching pulses.

V. SIMULATION MODEL

The Matlab-Simulink simulation block diagram of the proposed three-phase three-level series active filter based on fuzzy logic voltage controller is shown in Fig. 6. The model parameters used for simulation are: Voltage source Vs=220V, Frequency Fs=50Hz, Resistor Rs=0.1mΩ, Inductance Ls=0.0002mH, Resistor Rch =48.6Ω, Inductance Lch=40mH, Capacitance Cdc=3000µF, Resistor Rc=0.27mΩ, Inductance Lc=0.8mH.

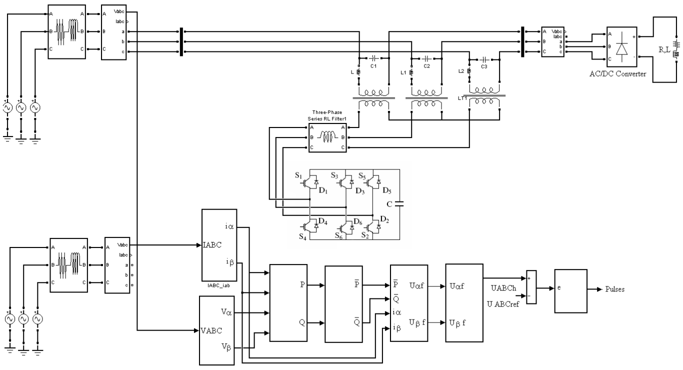


Figure 6. Three-phase series active power filter based on fuzzy voltage controller

VI. SIMULATION RESUTLS DISCUSSION

The purpose of the simulation is to show the effectiveness of the proposed series active power filter using fuzzy logic controller to compensate a several voltage harmonics introduced voluntary in the power grid. In the starts, we suppose that the three phase voltages are balanced and non-distorted.

The first voltage harmonic perturbation is introduced voluntarily at t1=0.1s to t2=0.16s. Between t2=0.16 s and t3=0.2s, the system is again at normal working condition. Between t3=0.2s and t4=0.26s the second harmonics perturbation is introduced. The first balanced distorted three-phase mains harmonic voltages perturbation is expressed as below:

$$v_{sa} = 311\sin(\omega t) + 141\sin(2\omega t) + 35\sin(4\omega t) + 14\sin(5\omega t)$$

$$v_{sb} = 311\sin(\omega t + \frac{4\pi}{3}) + 141\sin(2\omega t + \frac{4\pi}{3}) + 35\sin(4\omega t + \frac{4\pi}{3}) + 14\sin(5\omega t + \frac{4\pi}{3})$$

$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 141\sin(2\omega t + \frac{2\pi}{3}) + 35\sin(4\omega t + \frac{2\pi}{3}) + 14\sin(5\omega t + \frac{2\pi}{3})$$

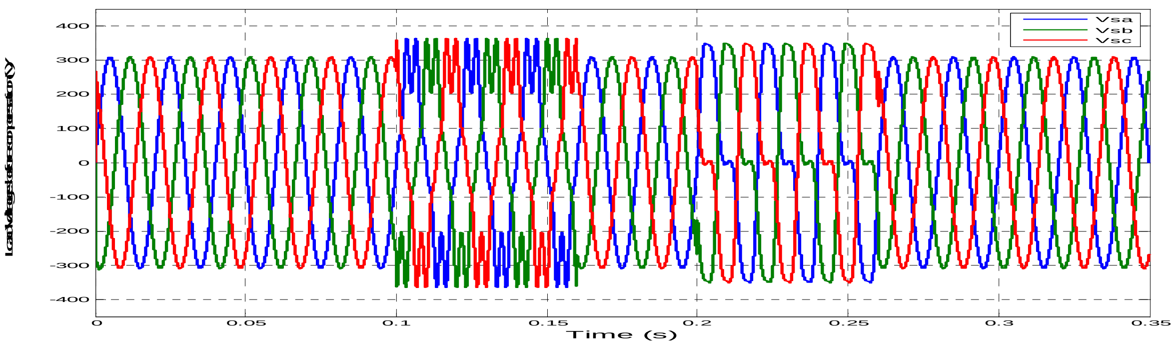
The second harmonic voltages perturbation is expressed by:

$$v_{sa} = 311\sin(\omega t) + 311/5\sin(5\omega t) + 311/7\sin(7\omega t)$$

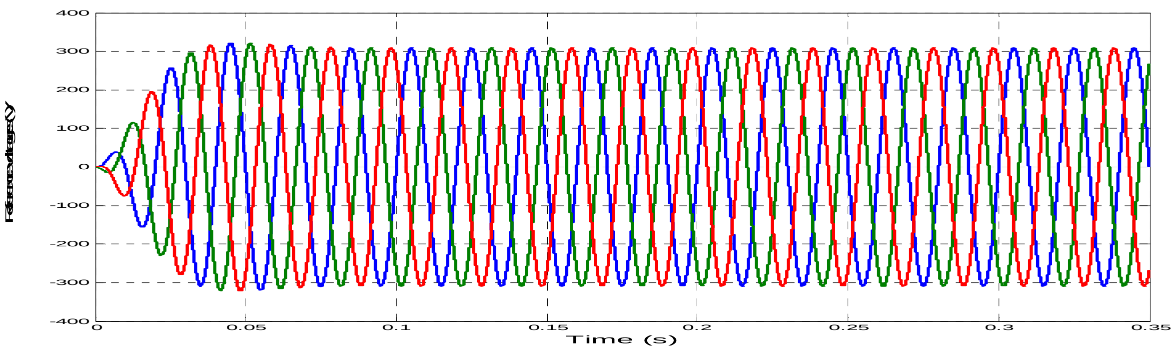
$$v_{sb} = 311\sin(\omega t - \frac{2\pi}{3}) + 311/5\sin(5\omega t + \frac{2\pi}{3}) + 311/7\sin(7\omega t - \frac{2\pi}{3})$$

$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 311/5\sin(5\omega t - \frac{2\pi}{3}) + 311/7\sin(7\omega t + \frac{2\pi}{3})$$

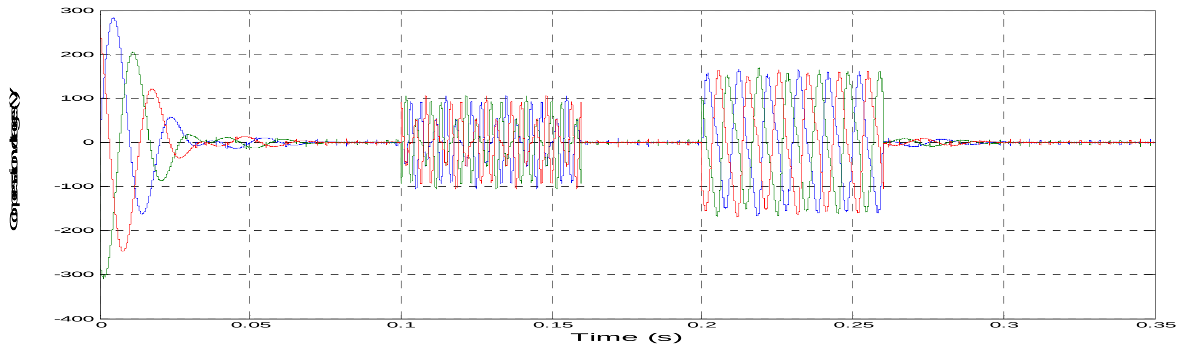
The series APF starts compensating voltage harmonics instantly. Fig. 7 shows the load voltage before series compensation, reference voltage, injected voltage delivered by series APF and the load voltage after compensation. The harmonic spectrum of the load voltage before and after compensation is shown respectively in Fig.8 to Fig.11.



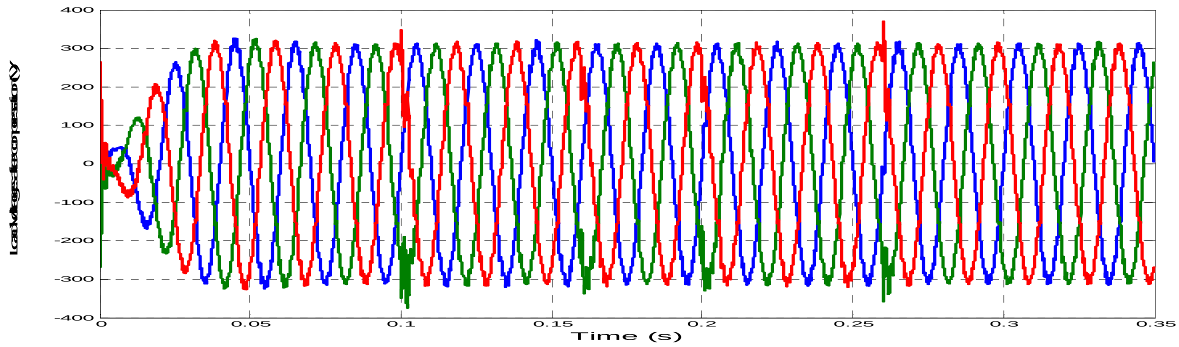
(a) Load voltage before compensation



(b) Reference voltages



(c) Compensation voltages



(d) Load voltage after compensation

Figure 7. Load voltage before compensation, reference voltages, injected voltages and load voltages after compensation

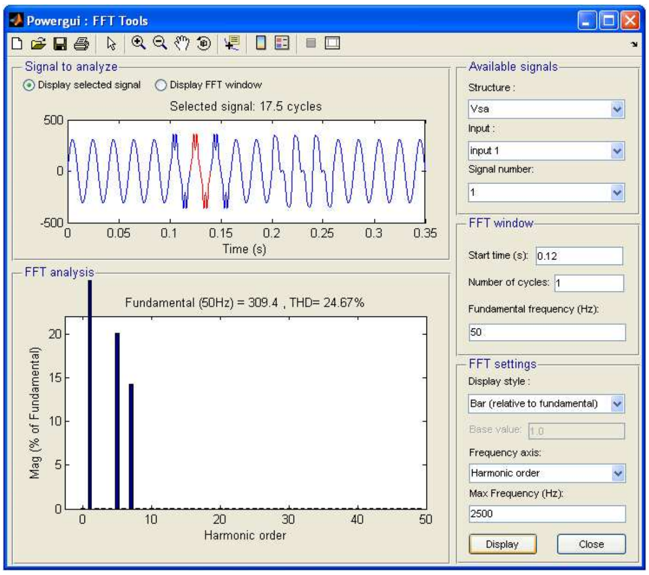


Figure 8. Load voltage harmonic spectrum without Series AF (THD=24.67%)

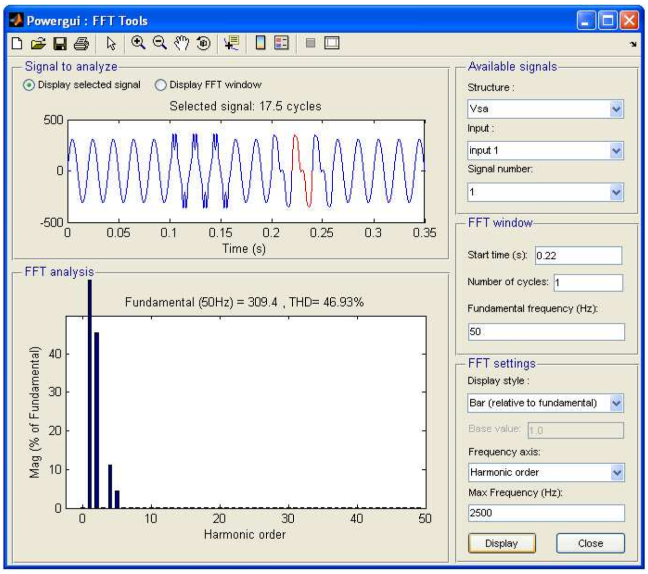


Figure 9. Load voltage harmonic spectrum without Series AF (THD=46.93%)

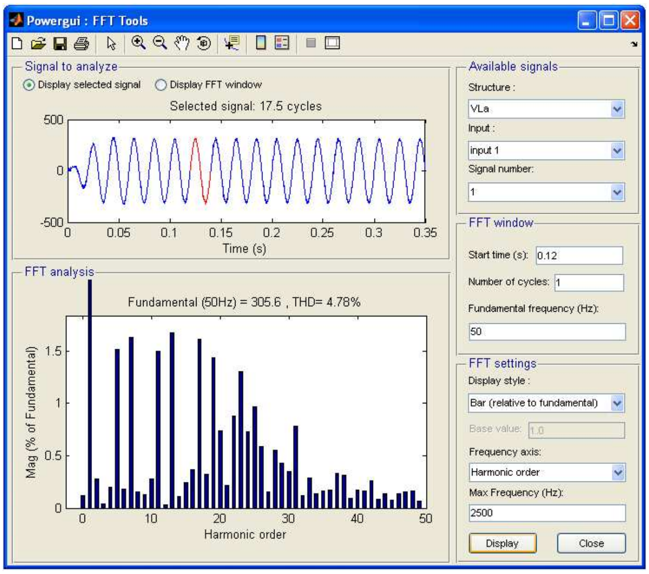


Figure 10. Load voltage harmonic spectrum with Series AF (THD=4.78%)

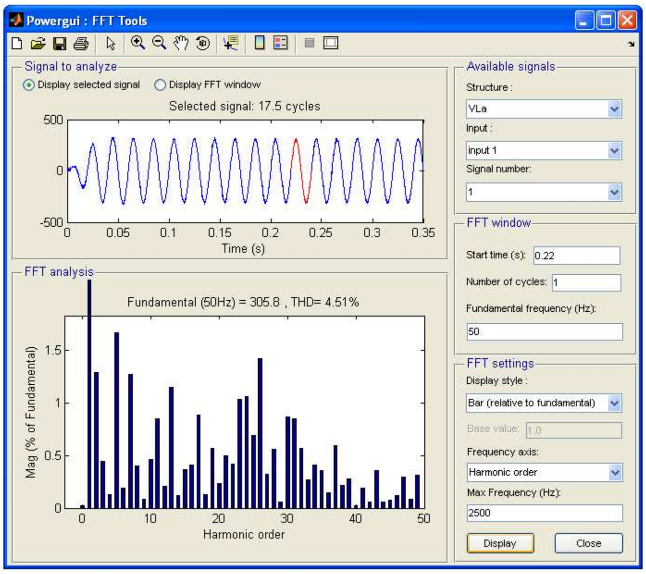


Figure 11. Load voltage harmonic spectrum with Series AF (THD=4.51%)

The performance of the proposed Series AF system is tested under two distorted voltage supply. The simulation result shows that the load voltage before compensation is highly distorted; its THD is equal to 24.67% for the first harmonics type and 46.93% for the second one. After compensation the THD is widely reduced to 4.78% and 4.51% with fast dynamic responses. The simulation results obtained using MATLAB-Simulink and SimPowerSystem show the effectiveness of the proposed series APF based on fuzzy voltage controller to ensure a pure sinusoidal voltage for sensible or critical loads at distorted supply network.

VII. Conclusion

To improve the power quality and reduce the source voltage harmonics delivered to sensible or critical loads, a new series active power filter configuration based on fuzzy logic voltage controller has been proposed in this paper. The control strategy used to determine compensation voltages is the PQ theory. The proposed series active filter compensates effectively the voltage harmonics with fast dynamic responses, the voltage delivered to critical or sensible loads is practically sinusoidal and without harmonics. The solution proposed in this article can be very interesting to equip power sensible loads especially if the voltage source is highly distorted. The MATLAB-Simulink results show that the load voltage harmonics is significantly reduced from 24.67% to 4.78% and from 46.93% to 4.51% in conformity with the IEEE standard Norms.

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Series Active Power Filter for Harmonic Voltage Compensation using two Control Strategies based on Fuzzy Control Techniques

Chennai Salim, Benchouia M-T and Goléa A

Abstract--**This paper presents a three-phase series active power filter for harmonic voltage compensation using two control strategies based on instantaneous reactive power theory. The conventional scheme is based on two-level voltage source inverter with on hysteresis controller. To simplify and improve the series APF capability, a fuzzy control technique is adopted in this work. Today fuzzy logic controllers are successfully employed in various industrial applications; their advantages are robustness and easy implementation. The proposed fuzzy voltage controller is designed to improve compensation capability of series active power filter by adjusting the voltage error using a fuzzy rule. The simulation is performed using MATLAB-Simulink and SimPowerSystem BlockSet Toolbox. The simulation results to validate harmonic voltage identification are presented and discussed.**

Index Terms*--*Series active power filter, Fuzzy logic voltage controller, Harmonics voltage, instantaneous reactive power theory.

I. INTRODUCTION

WITH the continuous proliferation of non linear loads, harmonic pollution is being considered as one of the major problems that degrade the power quality. Active power filters have been proposed as an interesting and high performance solution to improve the power quality [1]. Shunt active power filter is generally used to compensate current harmonics. Series active power filter is one of the control devices that feed modern industry with high quality power supply [2], it is used to compensate all types of voltage perturbations, such as voltage unbalances, sags, harmonics and voltage swells, these perturbations have harmful effects on the electric equipments [3].

The series active power filter is inserted in series between the load and the source voltage. Three single phase transformers are used to perform the series connection. The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [4], [5], to improve the Series APF performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic controllers. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. The fuzzy control does not need an accurate mathematical model of a plant. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. Thus, control design is simple since it is only based on if....then linguistic rules [6], [7], [8].

The investigation in this paper concentrates on the fuzzy control approaches for the three-phase series APF to compensate particularly harmonics voltage perturbation using two control strategies based on the instantaneous reactive power theory [9]. The performance of the proposed series active power filter is evaluated using Matlab-Simulink and SimPowerSystem Toolbox. The obtained results show the effectiveness of the proposed fuzzy control scheme compared to the hysteresis control.

II. SERIES ACTIVE POWER FILTER

The circuit configuration of the series active filter is shown in Fig. 1, the Series AF is inserted between the perturbed voltage source and a protected load. It is composed of three phase voltage source converter, L_fC_f filter to suppress switching ripples and series transformers which inject the compensating voltage to the line [10].

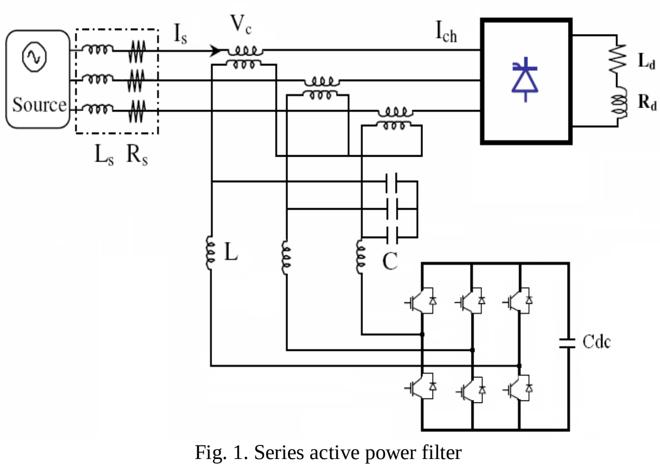

Fig. 1. Series active power filter

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III. CONTROL STRATEGIES

A. Harmonic voltage identification based on instantaneous reactive power theory PQ(I)

The proposed series active filter is adopted to compensate voltage harmonics. The first control strategy used for extracting the reference voltages of series active power filter is based on the p-q theory described in [11], [12].

We assume that the three-phase voltage source in the grid is symmetric and distorted:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2}U_n \sin(n\omega t+\theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2}U_n \sin\left[(n\omega t-\frac{2\pi}{3})+\theta_n\right] \\ \sum_{n=1}^{\infty} \sqrt{2}U_n \sin\left[(n\omega t+\frac{2\pi}{3})+\theta_n\right] \end{bmatrix} \quad (1)$$

Un and θn are respectively the rms voltage and initial phase angle, n is the harmonic order.

When n=1, it means three-phase fundamental voltage source:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sqrt{2}U_1 \sin(\omega t+\theta_1) \\ \sqrt{2}U_1 \sin\left[(\omega t-\frac{2\pi}{3})+\theta_1\right] \\ \sqrt{2}U_1 \sin\left[(\omega t+\frac{2\pi}{3})+\theta_1\right] \end{bmatrix} \quad (2)$$

Equation (1) is transformed into (α–β) reference frame:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = C_{32} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \sqrt{3} \begin{bmatrix} \sum_{n=1}^{\infty} U_n \sin(n\omega t+\theta_n) \\ \sum_{n=1}^{\infty} \mp U_n \sin(n\omega t+\theta_n) \end{bmatrix} \quad (3)$$

Where:

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (4)$$

Three-phase positive fundamental current template is constructed:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t-\frac{2\pi}{3}) \\ \sin(\omega t+\frac{2\pi}{3}) \end{bmatrix} \quad (5)$$

Equation (5) is transformed to (α–β) reference frame:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t \end{bmatrix} \quad (6)$$

According to the instantaneous reactive power theory [11], then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

Where DC and AC components are included:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p}+\tilde{p} \\ \bar{q}+\tilde{q} \end{bmatrix} \quad (8)$$

P and q are passed through low pass filter (LPF) and DC component are got:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \sqrt{3} \begin{bmatrix} U_1 \cos(\theta_1) \\ U_1 \sin(\theta_1) \end{bmatrix} \quad (9)$$

According to (7), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \quad (10)$$

As for DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} u_{\alpha f} & u_{\beta f} \\ u_{\beta f} & -u_{\alpha f} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} \quad (11)$$

The fundamental voltages in (α–β) reference frame are:

$$\begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (12)$$

The three-phase fundamental voltage is:

$$\begin{bmatrix} U_{af} \\ U_{bf} \\ U_{cf} \end{bmatrix} = C_{23} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \sqrt{2}U_1 \begin{bmatrix} \sin(\omega t+\theta_1) \\ \sin(\omega t+\theta_1-\frac{2\pi}{3}) \\ \sin(\omega t+\theta_1+\frac{2\pi}{3}) \end{bmatrix} \quad (13)$$

Where:

$$C23 = \begin{bmatrix} 1 & 0 \\ -1/2 & \frac{\sqrt{3}}{2} \\ -1/2 & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (14)$$

The block diagram of the harmonic voltage identification based on (p-q) theory is presented in Fig. 2.

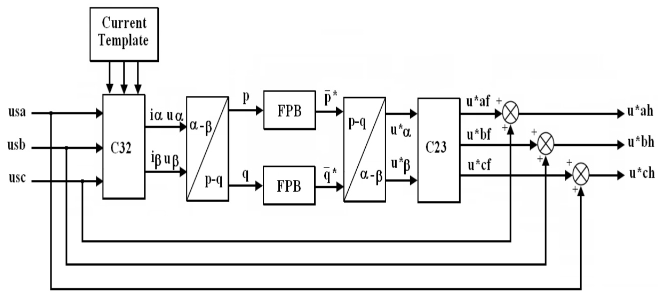


Fig. 2. Block diagram of voltages reference identification based on PQ(I)

B. Harmonic voltage identification based on instantaneous reactive power theory PQ(II)

When the three-phase load instantaneous voltages Ulu, Ulv, Ulw and currents Ilu, Ilv, Ilw, are transformed into two-phase (α–β) coordinates, two phase voltages $\overrightarrow{u_\alpha}$, $\overrightarrow{u_\beta}$ and currents $\overrightarrow{i_\alpha}$, $\overrightarrow{i_\beta}$ are respectively given by:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} = C_{32} \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{lu} \\ i_{lv} \\ i_{lw} \end{bmatrix} = C_{32} \begin{bmatrix} i_{lu} \\ i_{lv} \\ i_{lw} \end{bmatrix} \tag{16}$$

On the (α–β) plane, $\vec{u}$ can be considered to be composed of $\overrightarrow{u_\alpha}$ and $\overrightarrow{u_\beta}$ and $\vec{i}$ of $\overrightarrow{i_\alpha}$ and $\overrightarrow{i_\beta}$:

$$\begin{aligned} \vec{u} &= \overrightarrow{u_\alpha} + \overrightarrow{u_\beta} \\ \vec{i} &= \overrightarrow{i_\alpha} + \overrightarrow{i_\beta} \end{aligned} \tag{17}$$

Assume that u_p is the projection of $\vec{u}$ in the direction of $\vec{i}$ and u_q the projection of $\vec{u}$ in the vertical direction of $\vec{i}$; u_p and u_q can be represented by:

$$\begin{bmatrix} u_p \\ u_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \left(\sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \right) \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix}$$

$$\begin{bmatrix} u_p \\ u_q \end{bmatrix} = C_{pq} C_{32} \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} \tag{18}$$

Where C_{pq} is the pq transformation matrix, which executes the calculation to convert the two-phase voltages u_α and u_β into u_p and u_q. Ulu, Ulv and Ulw are the three-phase voltage source, the respective components $\overline{u_p}$ and $\overline{u_q}$ in u_p and u_q are corresponding to the positive sequence fundamental active and reactive components in three-phase voltages.

The fundamental components Uluf, Ulvf and Ulwf in load voltages can be obtained by an inverse transformation of (18):

$$\begin{bmatrix} U_{luf} \\ U_{lvf} \\ U_{lwf} \end{bmatrix} = \left(\sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \right) \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \begin{bmatrix} \overline{u_p} \\ \overline{u_q} \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} U_{luf} \\ U_{lvf} \\ U_{lwf} \end{bmatrix} = C_{23} C_{pq}^{-1} \begin{bmatrix} \overline{u_p} \\ \overline{u_q} \end{bmatrix} \tag{20}$$

Where C_{pq}^{-1} is the inverse matrix of C_{pq}, which executes the calculation to convert $\overline{u_p}$ and $\overline{u_q}$ back into (α–β) coordinates. Hence the voltage compensation can be calculated out as:

$$\begin{bmatrix} U_{luc} \\ U_{lvc} \\ U_{lwc} \end{bmatrix} = \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} - \begin{bmatrix} U_{luf} \\ U_{lvf} \\ U_{lwf} \end{bmatrix} \tag{21}$$

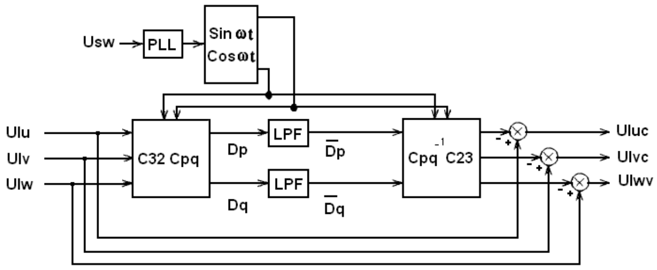


Fig. 3. Block diagram of voltages reference identification based on PQ(II)

IV. FUZZY LOGIC CONTROL

Fuzzy logic controllers (FLCs) have been interest a good alternative in more power electronics application. Their advantages are robustness, easy implementation and accept non-linearity [13], [14]. To benefit of these advantages a simple fuzzy logic voltage controller is proposed to control the Series APF. Fig. 4 shows a schematic block diagram of fuzzy inference system or fuzzy controller [15].

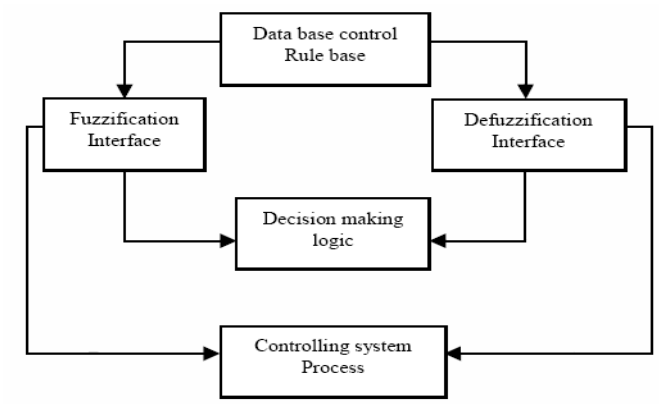


Fig. 4. Fuzzy inference system

The fuzzy voltage controller proposed in this paper is designed to improve compensation capability of APF by adjusting the voltage error using fuzzy rules. The desired inverter switching signals are determined according the error between the compensate voltages and reference voltages. In this case, the fuzzy logic voltage controller has two inputs, error e and change of error de and one output s. To convert it into linguistic variable, we use seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large). The membership functions used in fuzzification and defuzzification are shown in Fig. 5.

The fuzzy controller for every phase is characterized for the following:

- Seven fuzzy sets for each input,
- Seven fuzzy sets for output,
- Triangular and trapezoidal membership function for the inputs and output,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.

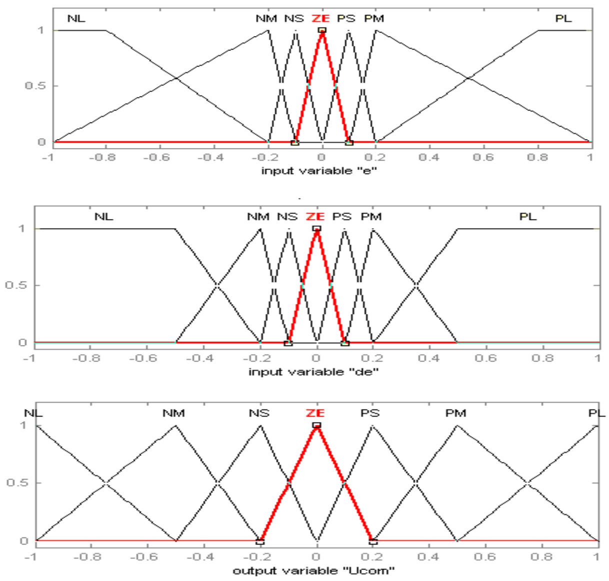


Fig. 5. Membership function for the inputs and output variables

The fuzzy rules are given by Table (1).

e de/dt	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	EZ
NM	NL	NM	NM	NS	NS	EZ	PS
NS	NM	NM	NS	NS	EZ	PS	PS
ZE	NM	NS	NS	EZ	PS	PS	PM
PS	NS	NS	EZ	PS	PS	PM	PM
PM	NS	EZ	PS	PS	PM	PM	PL
PL	EZ	PS	PS	PM	PM	PL	PL

Table (1) Fuzzy rules

The generation process of switching signals is given by Fig.6.

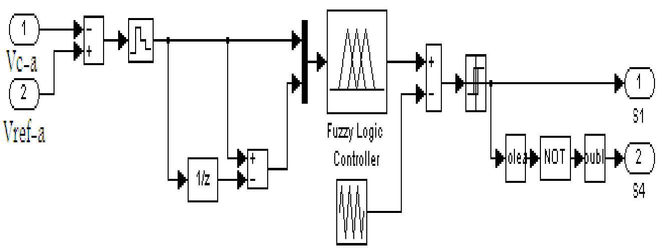


Fig. 6. Switching signals generation based on fuzzy controller

The controller calculates the difference between the injected voltage and the reference voltage that determines the reference voltage of the inverter. This fuzzy voltage is compared with carrying triangular waves and generates switching pulses.

V. Simulation Models

The bloc diagram schemes of the proposed series active power filter based on fuzzy logic voltage controller are shown in Figs. 7 and 8. The model parameters used for simulation are: Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_L =48.6Ω, Inductance L_L=40mH, Capacitance C_{dc}=3000µF, Resistor R_c=0.27mΩ, Inductance L_c=0.8mH.

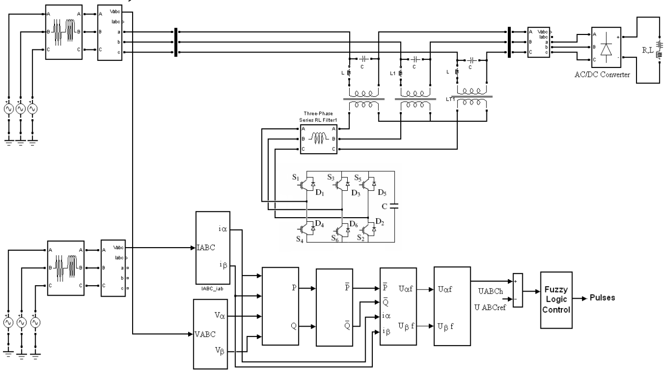


Fig. 7. Three-phase series active power filter using fuzzy voltage controller based on instantaneous reactive power theory PQ(I)

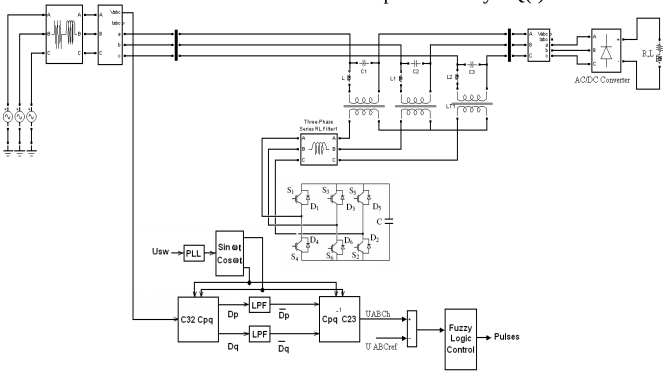


Fig. 8. Three-phase series active power filter using fuzzy voltage controller based on instantaneous reactive power theory PQ(II)

VI. Simulation Results and Discussion

The purpose of the simulation is to show the effectiveness of the proposed series active power filter using fuzzy logic controller to compensate a several voltage harmonics introduced voluntary in the power grid. In the starts, we suppose that the three phase voltages are balanced and non-distorted.

The first voltage harmonic perturbation is introduced voluntarily at t_1=0.1 sec to t_2=0.16 sec. Between t_2=0.16 sec and t_3=0.2 sec, the system is again at normal working condition. Between t_3=0.2sec and t_4=0.26sec the second harmonics perturbation is introduced. The first balanced distorted three-phase mains harmonic voltages perturbation is expressed as below:

$$v_{sa} = 311\sin(\omega t) + 311/5\sin(5\omega t) + 311/7\sin(7\omega t)$$

$$v_{sb} = 311\sin(\omega t - \frac{2\pi}{3}) + 311/5\sin(5\omega t + \frac{2\pi}{3}) + 311/7\sin(7\omega t - \frac{2\pi}{3})$$

$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 311/5\sin(5\omega t - \frac{2\pi}{3}) + 311/7\sin(7\omega t + \frac{2\pi}{3})$$

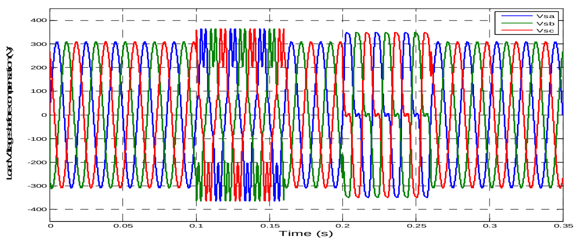
The second harmonic voltages perturbation is expressed by:

$$v_{sa} = 311\sin(\omega t) + 141\sin(2\omega t) + 35\sin(4\omega t) + 14\sin(5\omega t)$$

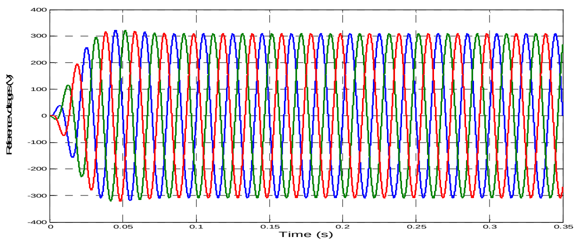
$$v_{sb} = 311\sin(\omega t + \frac{4\pi}{3}) + 141\sin(2\omega t + \frac{4\pi}{3}) + 35\sin(4\omega t + \frac{4\pi}{3}) + 14\sin(5\omega t + \frac{4\pi}{3})$$

$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 141\sin(2\omega t + \frac{2\pi}{3}) + 35\sin(4\omega t + \frac{2\pi}{3}) + 14\sin(5\omega t + \frac{2\pi}{3})$$

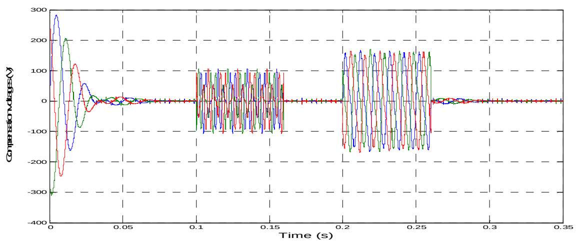
The series APF starts compensating voltage harmonics instantly. Fig. 9, shows the load voltage before series compensation, reference voltage, injected voltage delivered by series APF and the load voltage after compensation. The harmonic spectrums of the load voltage before compensation are shown respectively in Fig. 10 and Fig. 11. The harmonic spectrums of the load voltage after compensation are shown respectively in Fig. 12 to Fig. 15.



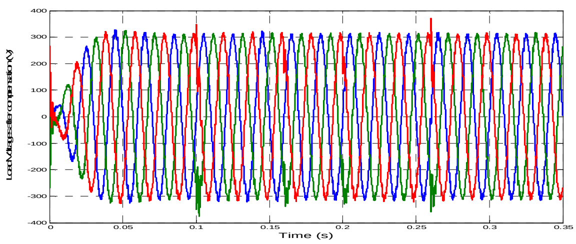
(a) Load voltage before compensation



(b) Reference voltages



(c) Compensation voltages



(d) Load voltage after compensation

Fig. 9. Load voltage before compensation, reference voltages, injected voltages and load voltages after compensation

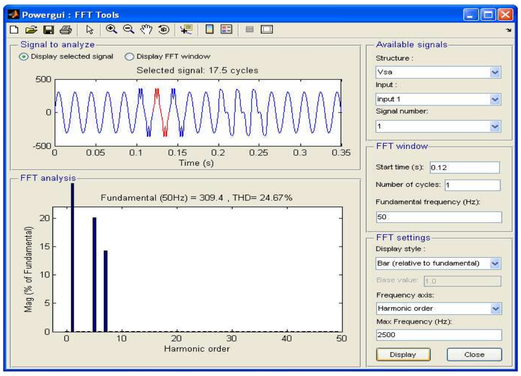


Fig. 10. Load voltage harmonic spectrum without Series AF THDv=24.67%

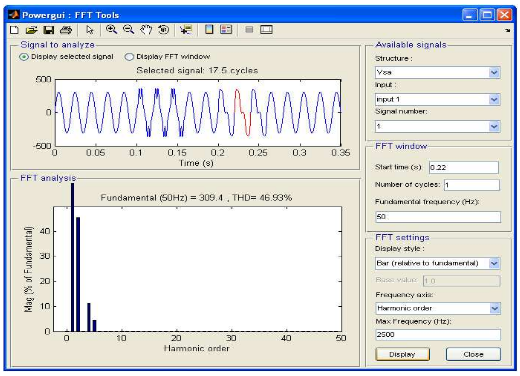


Fig. 11. Load voltage harmonic spectrum without Series AF: THDv=46.93%

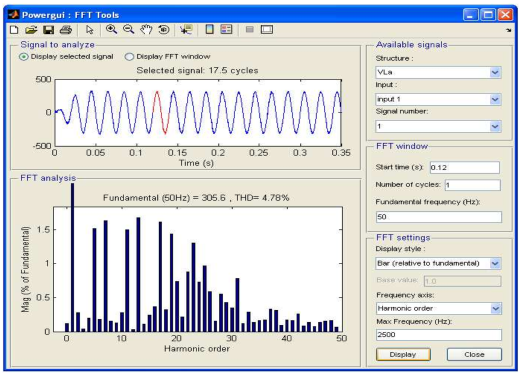


Fig. 12. Load voltage harmonic spectrum with Series AF using PQ(I): THDv=4.78%

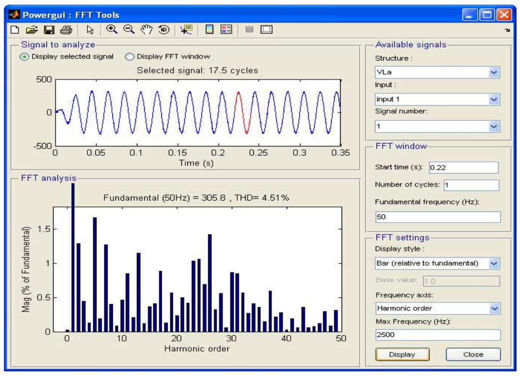


Fig. 13. Load voltage harmonic spectrum with Series AF using PQ(I): THDv=4.51%

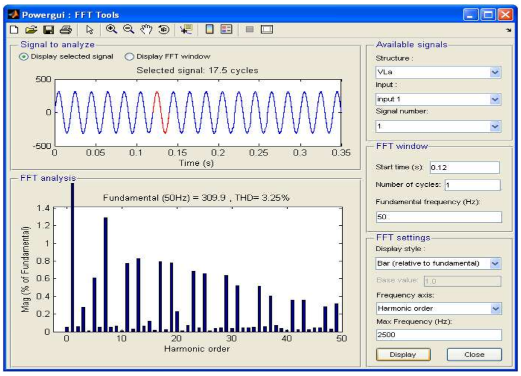


Fig. 14. Load voltage harmonic spectrum with Series AF using PQ(II): THDv=3.25%

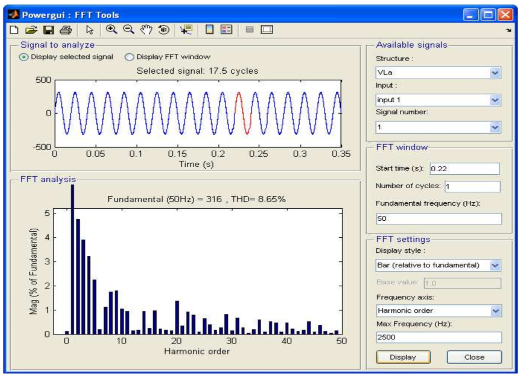


Fig. 15. Load voltage harmonic spectrum with Series AF using PQ(II): THDv=8.65%

The performance of the proposed Series AF system based on two control strategies is tested under two distorted voltage supply. The simulation result shows that the load voltage before compensation is highly distorted; its THD is equal to 24.67% for the first harmonics type and 46.93% for the second one. After compensation the THD is reduced to 4.78% and 4.51% for the first strategy and to 3.25% and 8.65% for the second strategy. The simulation results obtained using MATLAB-Simulink and SimPowerSystem show the effectiveness of the proposed series APF based on fuzzy control techniques to ensure a pure sinusoidal voltage for loads at distorted supply network.

The performances in terms of harmonics voltage elimination of the series APF based on the two strategies are summarized in Table I.

TABLE I HARMONICS COMPENSATION PERFORMANCES

Control Strategy	Harmonics (1) THD%=24.67%	Harmonics (2) THD%=46.93%
PQ(I)	THD%=4.78%	THD%=4.51%
PQ(II)	THD%=3.25%	THD%=8.65%

VII. CONCLUSION

To improve the power quality and reduce the source voltage harmonics delivered to critical loads, a series active power filter configuration based on fuzzy logic voltage controller has been proposed in this paper. The two control strategies adopted are based on the PQ theory. The proposed series active filter compensates effectively the voltage harmonics with fast dynamic responses, the voltage delivered to critical loads is practically sinusoidal and without harmonics. The solution proposed in this article can be very interesting to equip power sensible loads especially if the voltage source is highly distorted. The MATLAB-Simulink results show that the load voltage harmonics is significantly reduced from 24.67% to 4.78% and from 46.93% to 4.51% in the first cases and from 24.67% to 3.25% and from 46.93% to 8.65% for the second cases.

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Performances of Series Active Power Filter based on Hysteresis and Fuzzy Controllers to compensate Harmonic Voltage Perturbations using Instantaneous Reactive Power Strategy

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Abstract –**This paper presents a three-phase three-wire series active power filter for harmonic voltage compensation based on instantaneous reactive power strategy. The conventional scheme is based on two-level voltage source inverter with hysteresis controller. To simplify and improve the series APF capability, a fuzzy control technique is adopted in this work. Today fuzzy logic controllers are successfully employed in various industrial applications; their advantages are robustness and easy implementation. The proposed fuzzy voltage controller is designed to improve compensation capability of series active power filter by adjusting the voltage error using a fuzzy rule. The simulation is performed using MATLAB-Simulink and SimPowerSystem BlockSet Toolbox. The obtained simulation results validate that the proposed Series AF compensate perfectly the harmonic voltage.**

Keywords – Three-level (NPC) series active power filter, Fuzzy logic control, Harmonics voltage compensation, instantaneous reactive power theory

I. Introduction

With the continuous proliferation of non linear loads, harmonic pollution is being considered as one of the major problems that degrade the power quality. Active power filters have been proposed as an interesting and high performance solution to improve the power quality [1]. Shunt active power filter is generally used to compensate current harmonics. Series active power filter is one of the control devices that feed modern industry with high quality power supply [2], it is used to compensate all types of voltage perturbations, such as voltage unbalances, sags, harmonics and voltage swells, these perturbations have harmful effects on the electric equipments [3].

The series active power filter is inserted in series between the load and the source voltage. Three single phase transformers are used to perform the series connection. The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [4,5], to improve the Series APF performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic controllers. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. The fuzzy control does not need an accurate mathematical model of a plant. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. This control technique relies on the human capability to understand the system's behaviour and is based on qualitative control rules. Thus, control design is simple since it is only based on if....then linguistic rules [6],[7],[8].

The investigation in this paper concentrates on the fuzzy control approaches for the three-phase series APF to compensate particularly harmonics voltage perturbation using instantaneous reactive power theory control strategy [9]. The performance of the proposed series active power filter is evaluated using Matlab-Simulink and SimPowerSystem Toolbox.

II. Series Active Power Filter

The circuit configuration of the series active filter is shown in Fig. 1, the Series AF is inserted between the perturbed voltage source and a protected load. It is composed of three phase voltage source converter, LfCf filter to suppress switching ripples and series transformers which inject the compensating voltage to the line [10].

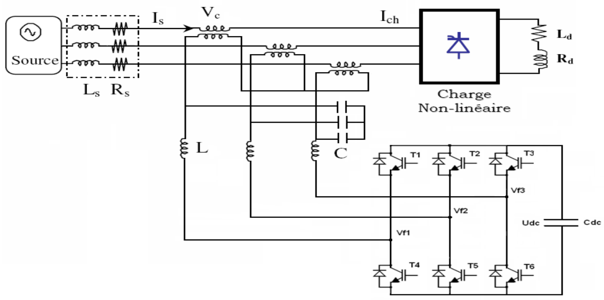


Fig. 1 Series active power filter

III. Control Strategy

The proposed series active filter is adopted to compensate voltage harmonics. The control strategy used for extracting the reference voltages of series active power filter is based on the p-q theory described in [11],[12],[13],[18].

We assume that the three-phase voltage source in the grid is symmetric and distorted:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t - \frac{2\pi}{3}) + \theta_n\right] \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t + \frac{2\pi}{3}) + \theta_n\right] \end{bmatrix} \quad (1)$$

Un and θn are respectively the rms voltage and initial phase angle, n is the harmonic order.
When n=1, it means three-phase fundamental voltage source:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sqrt{2} U_1 \sin(\omega t + \theta_1) \\ \sqrt{2} U_1 \sin\left[(\omega t - \frac{2\pi}{3}) + \theta_1\right] \\ \sqrt{2} U_1 \sin\left[(\omega t + \frac{2\pi}{3}) + \theta_1\right] \end{bmatrix} \quad (2)$$

Equation (1) is transformed into (α–β) reference frame:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = C_{32} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \sqrt{3} \begin{bmatrix} \sum_{n=1}^{\infty} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \mp U_n \sin(n\omega t + \theta_n) \end{bmatrix} \quad (3)$$

Where:

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (4)$$

Three-phase positive fundamental current template is constructed:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (5)$$

Equation (5) is transformed to (α–β) reference frame:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t \end{bmatrix} \quad (6)$$

According to the instantaneous reactive power theory [11], then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

Where DC and AC components are included:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \quad (8)$$

P and q are passed through low pass filter (LPF) and DC component are got:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \sqrt{3} \begin{bmatrix} U_1 \cos(\theta_1) \\ U_1 \sin(\theta_1) \end{bmatrix} \quad (9)$$

According to (7), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \quad (10)$$

As for DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} u_{\alpha f} & u_{\beta f} \\ u_{\beta f} & -u_{\alpha f} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} \quad (11)$$

The fundamental voltages in (α–β) reference frame are:

$$\begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (12)$$

The three-phase fundamental voltage is:

$$\begin{bmatrix} U_{af} \\ U_{bf} \\ U_{cf} \end{bmatrix} = C_{23} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \sqrt{2} U_1 \begin{bmatrix} \sin(\omega t + \theta_1) \\ \sin(\omega t + \theta_1 - \frac{2\pi}{3}) \\ \sin(\omega t + \theta_1 + \frac{2\pi}{3}) \end{bmatrix} \quad (13)$$

Where:

$$C23 = \begin{bmatrix} 1 & 0 \\ -1/2 & \frac{\sqrt{3}}{2} \\ -1/2 & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (14)$$

The block diagram of the harmonic voltage identification based on (p-q) theory is presented in Fig.2.

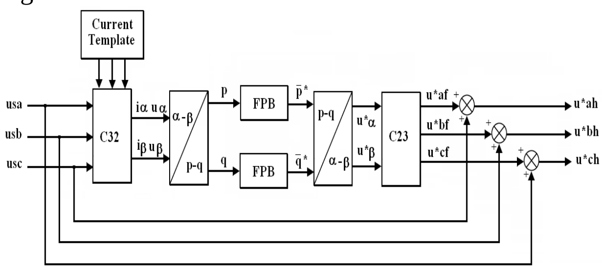


Fig. 2 Block diagram of voltages reference identification

III. FUZZY LOGIC CONTROL

Fuzzy logic controllers (FLCs) have been interest a good alternative in more power electronics application. Their advantages are robustness, easy implementation and accept non-linearity [14],[15]. To benefit of these advantages a simple fuzzy logic voltage controller is proposed to control the Series APF.

The fuzzy voltage controller proposed in this paper is designed to improve compensation capability of APF by adjusting the voltage error using fuzzy rules.

The desired inverter switching signals are determined according the error between the compensate voltages and reference voltages. In this case, the fuzzy logic voltage controller has two inputs, error e and change of error de and one output s. To convert it into linguistic variable, we use seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large). The membership functions used in fuzzification and defuzzification are shown in Fig. 3.

The fuzzy controller for every phase is characterized for the following:

- Seven fuzzy sets for each input,
- Seven fuzzy sets for output,
- Triangular and trapezoidal membership function for the inputs and output,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.

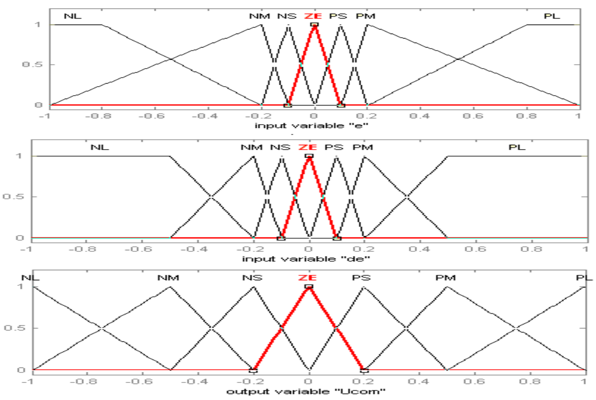


Fig. 3 Membership function (inputs and output variables)

The fuzzy rules are given by Table (1).

e / de/dt	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	EZ
NM	NL	NM	NM	NS	NS	EZ	PS
NS	NM	NM	NS	NS	EZ	PS	PS
ZE	NM	NS	NS	EZ	PS	PS	PM
PS	NS	NS	EZ	PS	PS	PM	PM
PM	NS	EZ	PS	PS	PM	PM	PL
PL	EZ	PS	PS	PM	PM	PL	PL

Table (1) Fuzzy rules

The generation process of switching signals is given by Fig.4.

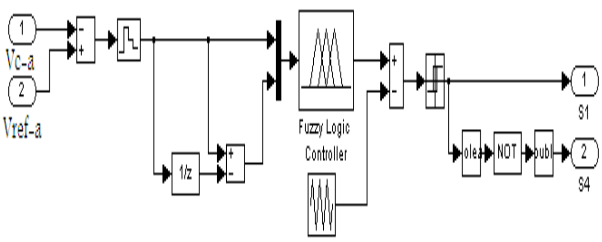


Fig. 4 Fuzzy controller

The controller calculates the difference between the injected voltage and the reference voltage that determines the error voltage, this error voltage pass through fuzzy controller. The fuzzy voltage error is compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses [16],[17].

IV. Simulation Model

The Matlab-Simulink simulation block diagram of the proposed series active power filter based on fuzzy logic voltage controller is shown in Figure (5).

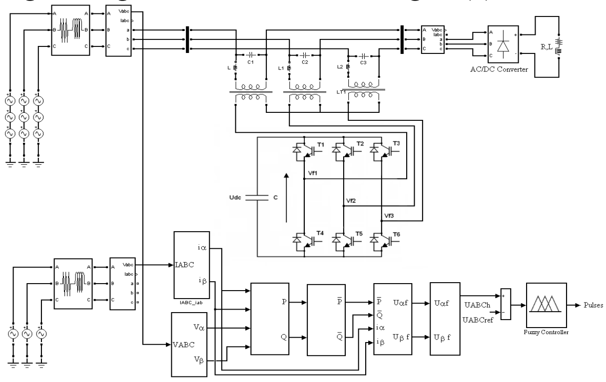


Fig. 5 Series active power filter based on instantaneous reactive power strategy using fuzzy controller

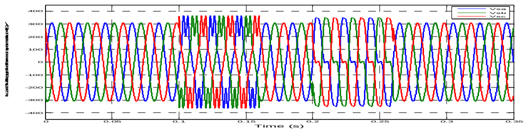
The model parameters used for simulation are: Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_L =48.6Ω, Inductance L_L=40mH, Capacitance C_{dc}=3000µF, Resistor R_c=0.27mΩ, Inductance L_c=0.8mH.

V. Simulation Results and Discussion

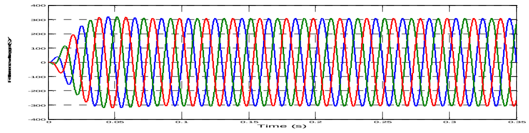
The purpose of the simulation is to show the effectiveness of the proposed series active power filter using fuzzy logic controller to compensate a several voltage harmonics introduced voluntary in the power grid. In the starts, we suppose that the three phase voltages are balanced and non-distorted.

The first voltage harmonic perturbation is rich on 5 and 7 component harmonics, it is introduced voluntarily at t1=0.1 sec to t2=0.16 sec. Between t2=0.16 sec and t3=0.2 sec, the system is again at normal working condition. The second harmonic voltages perturbation is rich on 2, 4 and 5 component harmonics, it is introduced between t3=0.2sec and t4=0.26sec.

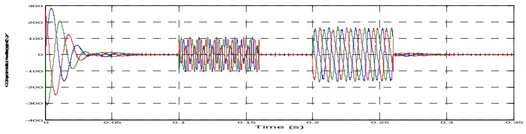
The series APF starts compensating voltage harmonics instantly. Fig. 6 shows the load voltage before series compensation, reference voltage, injected voltage delivered by series APF and the load voltage after compensation. The harmonic spectrum of the load voltage before and after compensation is shown respectively in Fig.6 to Fig.12.



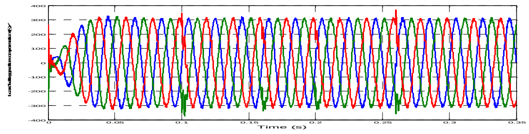
(a) Load voltage before compensation



(b) Reference voltages



(c) Compensation voltages (d)



(d) Load voltage after compensation

Fig. 6 Load voltage before compensation, reference voltages, injected voltages and load voltages after compensation

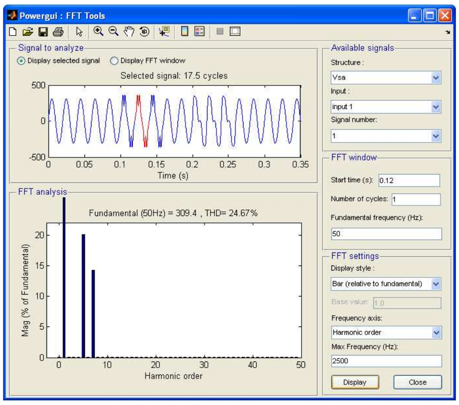


Fig. 7 Load voltage harmonic spectrum without Series AF (THDv=24.67%)

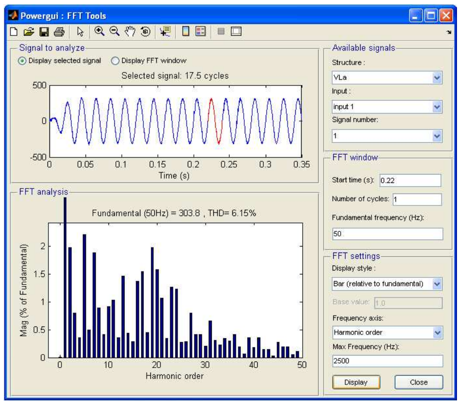


Fig. 10 Load voltage harmonic spectrum with Series AF-Hysteresis controller (THDv=6.15%)

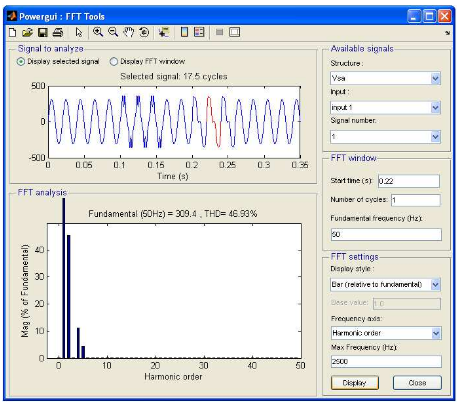


Fig. 8 Load voltage harmonic spectrum without Series AF (THDv=46.93%)

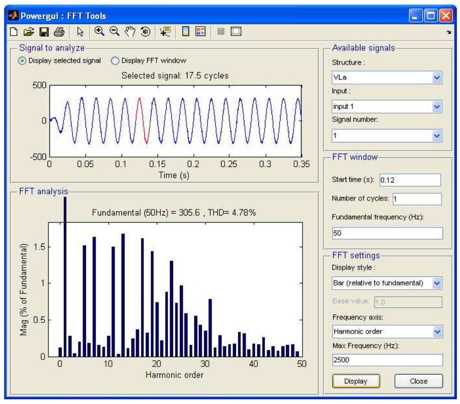


Fig. 11 Load voltage harmonic spectrum with Series AF using fuzzy controller (THDv=4.78%)

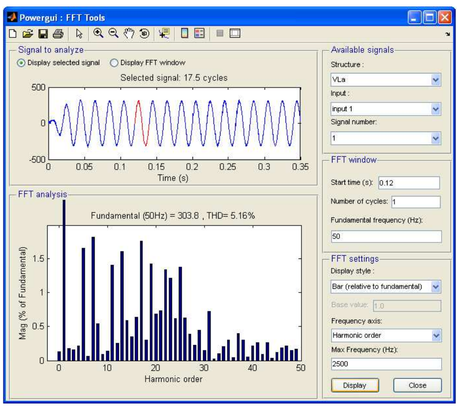


Fig. 9 Load voltage harmonic spectrum with Series AF-Hysteresis controller (THDv=5.16%)

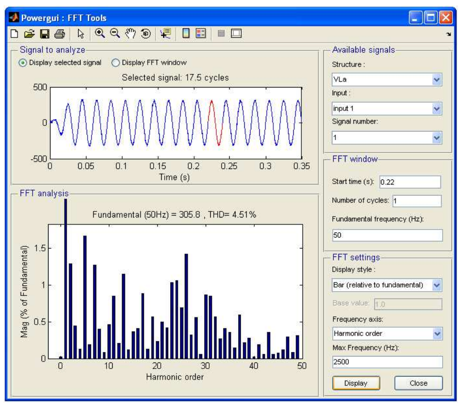


Fig. 12 Load voltage harmonic spectrum with Series AF using fuzzy controller (THDv=4.51%)

The performance of the proposed Series AF system is tested under two distorted voltage supply using hysteresis and fuzzy controllers. The simulation result shows that the load voltage before compensation is highly distorted; its THDv is equal to 24.67% for the first harmonics type and 46.93% for the second one. After compensation the THDv is widely reduced to 5.16% and 6.15% for the hysteresis controller and to 4.78% and 4.51% for the fuzzy system with fast dynamic responses. The simulation results obtained using MATLAB-Simulink and SimPowerSystem show the effectiveness of the proposed series APF based on fuzzy voltage controller to suppress harmonic voltage. The performances of the two controllers are summarized in Table (1).

Controller	PQ Control strategy	
	Harmonics (1) THD%=24.67%	Harmonics (2) THD%=46.93%
Hysteresis	THD%=5.16%	THD%=6.15%
Fuzzy	THD%=4.78%	THD%=4.51%

Table (1) Harmonics compensation performances

VI. Conclusion

To improve the power quality and reduce the source voltage harmonics delivered to sensible loads, a new series active power filter configuration based on fuzzy logic voltage controller has been proposed in this paper. The control strategy used to determine compensation voltages is the PQ theory. The proposed series active filter compensates effectively the voltage harmonics with fast dynamic responses, the voltage delivered to sensible loads is practically sinusoidal and without harmonics. The solution proposed in this article can be very interesting to equip power sensible loads especially if the voltage source is highly distorted. The MATLAB-Simulink results show that the load voltage harmonics is significantly reduced in conformity with the IEEE standard Norms.

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Shunt Active Power Filter Performances based on Three-Level (NPC) Inverter to Compensate Current Harmonics using Intelligent Controllers

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Abstract — **This paper presents a three-phase three-wire shunt active power filter based on three-level (NPC) inverter using two intelligent controllers to compensate current harmonics generated by non-linear loads. Shunt active filter is the best solution to eliminate harmonics drawn from nonlinear load especially for low power system. The conventional scheme is based on the two level inverter controlled by hysteresis controller, this configuration presents some drawbacks such us high inverse voltage applied to power components, degraded quality of the output voltage inverter waveforms, etc. Today three-level (NPC) inverter and intelligent controllers are widely used in different industrial applications. To take advantages of these inverter topology and AIC performance a two new control schemes of shunt active filter system are proposed in this work. The control strategy adopted is the synchronous reference current detection method. The numerical simulation is developed and performed using MATLAB-Simulink and SimPowerSystems Toolbox. The simulation results obtained from complete structure including control and power circuits show the effectiveness of the proposed shunt active power filter based on intelligent controllers.**

Keywords — **Shunt active filter, Intelligent controllers, ANNs, FLC, Three-level (NPC) inverter, Harmonic currents compensation.**

I. INTRODUCTION

With the proliferation of nonlinear power electronics loads, the problem of harmonic is severity, which influences the power quality of power grid. Passive power filter is a traditional harmonic restraint method. The passive filtering is a simple way to eliminate the harmonic currents. However, it does not allow to completely eliminating all of them and has many drawbacks such as series or parallel resonance with the system impedance [1].

Active filter is used, these last years, to improve power quality on the load side from the grid current, by injecting compensating currents [2]. The performance of an active filter mainly depends on the reference current generation strategy, hysteresis or PWM control, topology of the power converter, etc…

The controller is the main part of any active power filter operation and has been a subject of many researches in recent years. Among the various current control techniques, hysteresis current control is the most extensively used technique. It is easy to realize with high accuracy and fast response. In the hysteresis control technique the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteretic controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. To improve the control performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic and artificial neural network controllers [3],[4]. This paper presents a two novel control scheme for three-level (NPC) shunt active filter based on fuzzy and ANN's controllers. The model and numerical simulation in transient and steady-state conditions are developed and performed using Matlab-Simulink and SimPowerSystem Toolbox.

II. SHUNT ACTIVE FILTER

The basic block diagram including non linear load compensation principle of a shunt active power filters based on three-level (NPC) inverter is shown in Fig.1. It is controlled to draw/supply a compensated current from/to the utility, such that it cancels harmonic currents of the non-linear load and makes the source current in phase with the different waveforms. The current drawn from the power system at the coupling point of the shunt APF will result sinusoidal [5],[6].

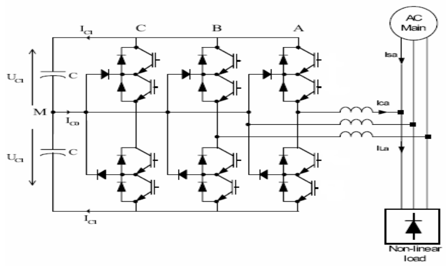


Fig.1 Three-level (NPC) Shunt active filter

III. CONTROL STRATEGY

A. Synchronous current detection method

The control strategy is inspired of the synchronous detection reference currents method [7]. It is based on the measuring of the source voltages (v_{sa}, v_{sb}, v_{sc}) given by (1) :

$$v_{sa}(t) = V_{sm}.\sin(\omega t)$$
$$v_{sb}(t) = V_{sm}.\sin(\omega t - \frac{2\pi}{3}) \quad (1)$$
$$v_{sa}(t) = V_{sm}.\sin(\omega t - \frac{4\pi}{3})$$

The maximum amplitude of the current supplied by the filter I^*_{smax} is given by (2):

$$I^*_{s\max} = I^*_{smp} + I^*_{smd} \quad (2)$$

With :

$$I^*_{smp} = \frac{2}{3}\frac{P_{moy}}{V_{sm}} \quad (3)$$

I^*_{smd} is the component current which maintains the DC voltage across the capacitor C_{cd} [8]. The reference currents must be sinusoidal and in phase with the voltage source. The desired current source AC can be calculated by multiplying the maximum amplitude of the current source of sinusoidal signals unit. These unit signals are given by (4):

$$i_{ua}(t) = v_{sa}/V_{sm}$$
$$i_{ub}(t) = v_{sb}/V_{sm} \quad (4)$$
$$i_{uc}(t) = v_{sc}/V_{sm}$$

$$i^*_{sa}(t) = I^*_{sm}.i_{ua}$$
$$i^*_{sb}(t) = I^*_{sm}.i_{ub} \quad (5)$$
$$i^*_{sc}(t) = I^*_{sm}.i_{uc}$$

The difference between the current references and the current drawn by the load can generate the three compensation current (i^*_{ca}, i^*_{cb} et i^*_{cc}) :

$$i^*_{ca} = i^*_{sa} - i_{La}$$
$$i^*_{cb} = i^*_{sb} - i_{Lb} \quad (6)$$
$$i^*_{cc} = i^*_{sc} - i_{Lc}$$

Fig.2 shows the principle scheme of the synchronous current detection method.

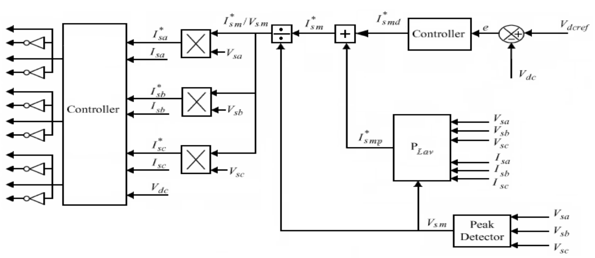


Fig.2 Synchronous current detection method control strategy principle

To compensate the inverter losses and maintain the dc-link voltage Udc constant, a proportional integral controller is used to obtain the compensation current I*smd. The control loop compares the measured voltage Udc with the reference voltage Udc-ref and generates corresponding current I*smd given by [9],[10]:

$$I^*_{smd} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \quad (7)$$

Where kp and ki are the proportional and integral gains of the PI controller and EUdc = (Udc-ref–Udc) is the DC bus voltage error.

IV. INTELLIGENT CURRENT CONTROLLERS

A. Fuzzy logic current controller

The main component of an active filter is the current controller. Generally the classical hysteresis controller is used to generate pulses to the PWM inverter; it is very stable and generates a minimum noise.

Recently, fuzzy logic controllers (FLCs) have been interest a good alternative in more application. The advantage of fuzzy systems are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, and they are more robust than conventional nonlinear controllers [11], [12].

Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. To develop the rules of the fuzzy logic, we need good understand of the process to be controlled, but it does not require a complicated mathematical model. The desired switching signals for the filter inverter circuit are determined according to the error in the filter current. In this case, the fuzzy logic current controller has two inputs, named error *e* and change of error *de* and one output named *s*. Here the error *e* and change of error *de* are the input variable for the system. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig. 3 shows the membership functions used in fuzzification.

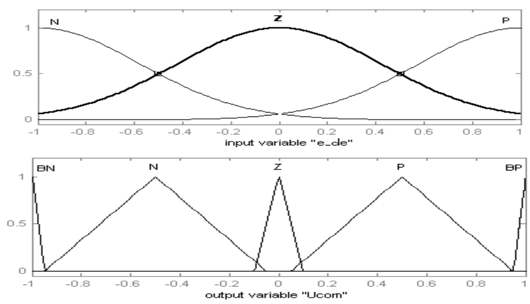


Figure 3: Membership function for the inputs and output variables

The fuzzy controller for every phase is characterized for the following:

- Three fuzzy sets for each input,
- Three fuzzy sets for each output,
- Triangular and trapezoidal membership functions,
- Implication using the “min” operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication.
- Defuzzification using the “centroid” method.

The linguistic rules for the fuzzy current controller are as follows:

1. If error is Negative and error rate is Negative Then output is Big Negative,
2. If error is Zero and error rate is Negative Then output is Positive,
3. If error is Positive and error rate is Negative Then output is Big Positive,
4. If error is Negative and error rate is Negative Then output in Big Negative,
5. If error is Zero and error rate is Zero Then output is Zero,
6. If error is Positive and error rate is Zero Then output is Big Positive,
7. If error is Negative and error rate is Positive Big Then output is Big Negative,
8. If error is Zero and error rate is Positive Then output is Negative,
9. If error is Positive and error rate is Positive Then output is Big Positive.

The generation process of switching signals is given by Fig.4.

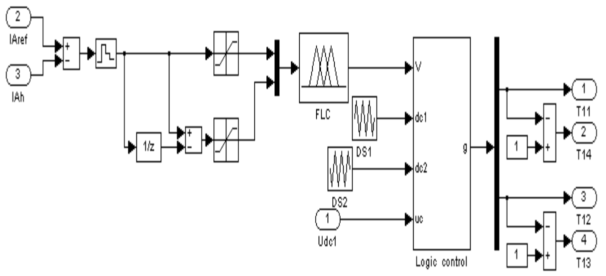


Fig.4 Generation process of switching signals

Fig.5 shows the Matlab-Simulink simulation block diagram of the proposed fuzzy current controller for the three-phase shunt active filter.

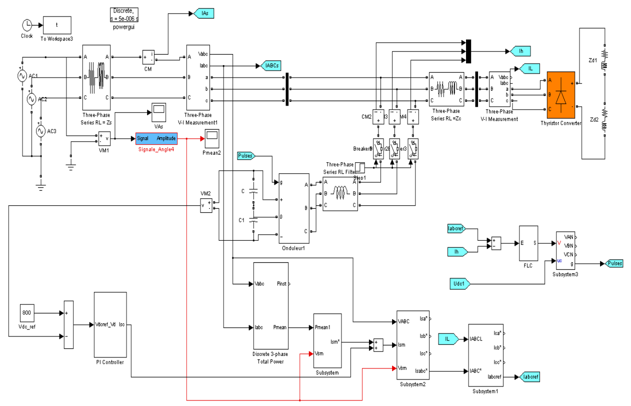


Fig.5 Shunt active filter based on Fuzzy current controller

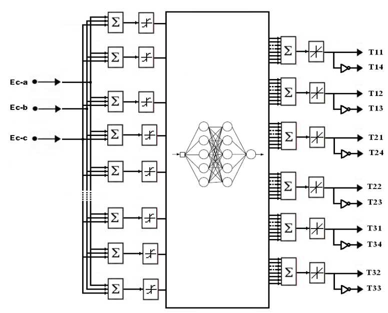
B. Artificial neural network current controller

Artificial Neural Networks have provided an alternative modeling approach for power system applications. The MLPN is one of the most popular topologies in use today. This network consists of a set of input neurons, output neurons and one or more hidden layers of intermediate neurons. Data flows into the network through the input layer, passes through the hidden layers and finally flows out of the network through the output layer. The network thus has a simple interpretation as a form of input-output model, with network weights as free parameters. The use and training of MLPNs is well understood [13].

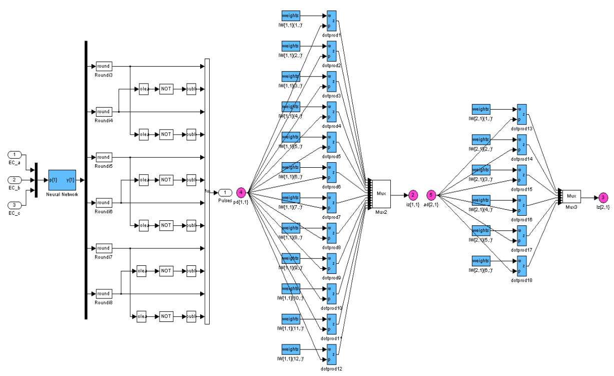
The objective of the training is to modify weight matrices W and V such that the ANN function approximates the plant function and the error e between the desired function output y and the ANN output $\hat{y}$ is minimal. The training cycle has two distinct paths:

- Forward propagation: It is the passing of inputs through the neural network structure to its output.
- Error back-propagation: It is the passing of the output error to the input in order to estimate the individual contribution of each weight in the network to the final output error. The weights are then modified so as to reduce the output error.

To be able to produce the correct output data, the network was trained with an improved algorithm, during the learning process the error function was minimized with an increasing number of training epochs. The artificial neural network current controller to use for the three-level inverter shunt active filter is shown in Figure 6. The input pattern is the error values (E_{ca}, E_{cb} and E_{cc}) between the measured filter currents (i_{fa}, i_{fb} and i_{fc}) and the compensating reference currents (i_{fa}^*, i_{fb}^* and i_{fc}^*) whereas the outputs values are the switching states T_{11}, T_{12}, T_{21}, T_{22}, T_{31} and T_{32}. The hidden layer contains 12 neurons with a sigmoid activation function and the output layer contains six neurons with a linear activation function. The network was trained with 10000 training examples using Levenberg-Marquardt back propagation algorithm.



a: ANN block diagram



b: Simulink ANN controller model

Fig. 6 Artificial Neural Network controller

Fig.7 shows the Matlab-Simulink simulation block diagram of the proposed ANN controller for the three-phase shunt active filter.

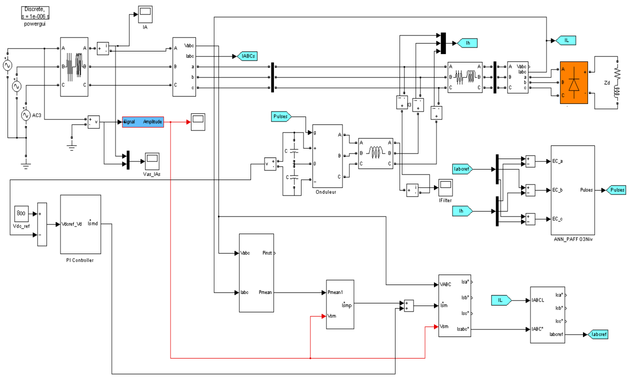


Fig.7 Shunt active filter using ANN current controller

V. SIMULATIONS

The purpose of the simulation is to show the effectiveness of the shunt active filter based on intelligent (fuzzy and ANN) current controllers to reducing the current harmonics produced on the load side under ideal voltages conditions. The model parameters used for simulation are: Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_{ch} =48.6Ω, Inductance L_{ch}=40mH, DC Voltage U_{dc} =800V, Capacitance C_1=C_2=300uF, Resistor R_c=0.27m Ω, Inductance L_c=0.8mH.

A) *Simulation results using ANN current controller*

Figure 8 shows the line voltage and the line current without APF. Figure 9 shows the corresponding source current harmonic spectrum before compensation. The load current, the injected current and the DC voltage across capacitor before and after shunt active filter operation are shown in Figure 10. Figure 11 shows the harmonic spectrum of the source current after compensation. Finally, the source current and the corresponding source voltage are presented simultaneously in Figure 12.

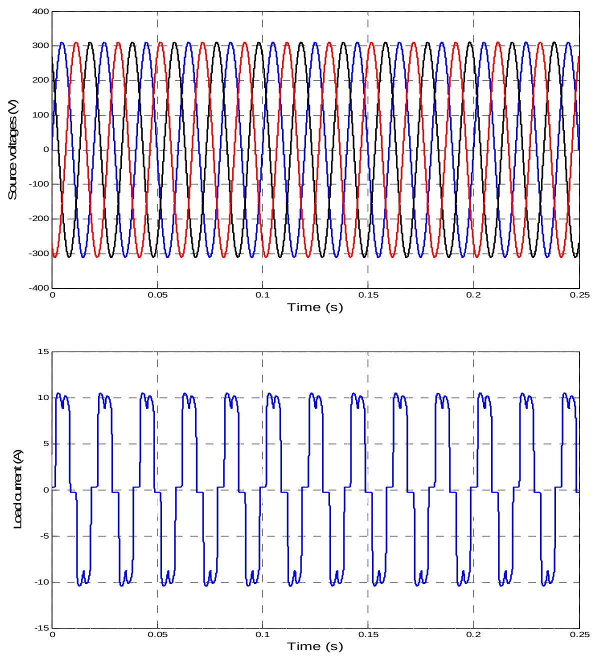


Fig. 8 Source voltages and line current before compensation

The source current is highly distorted and rich on harmonics. It is not in phase with the source voltage, the power factor is poor with high consummation of reactive power.

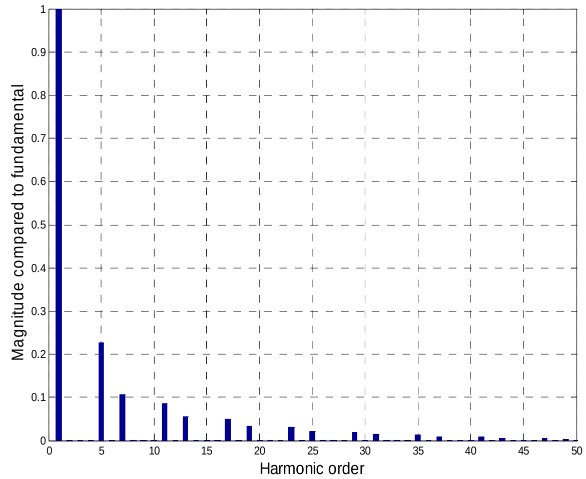


Fig. 9 Spectrum of source current without APF (THD=27.74%)

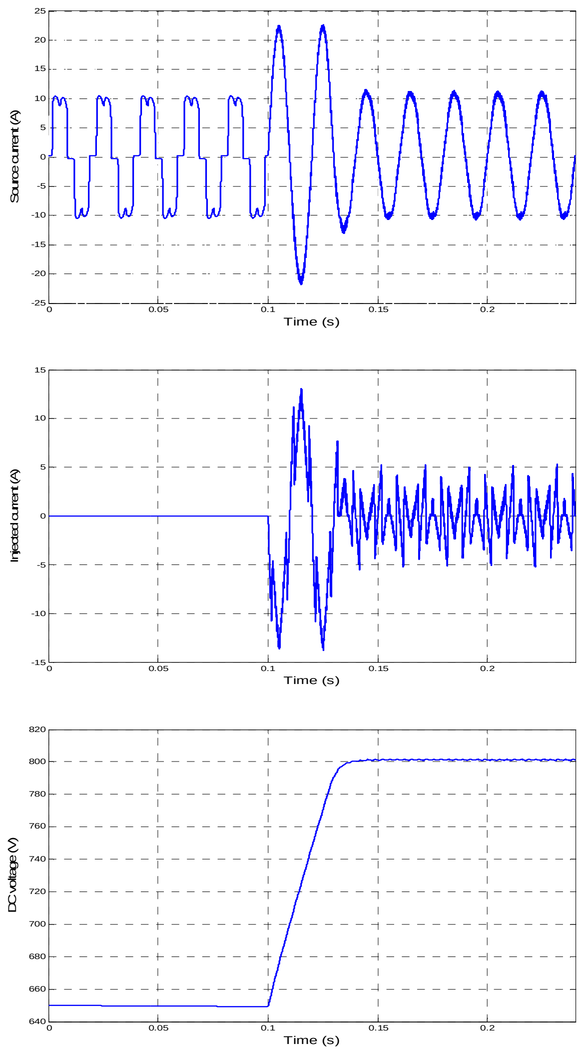


Fig. 10 Line current, injected current and DC voltage before and after compensation using ANN controller

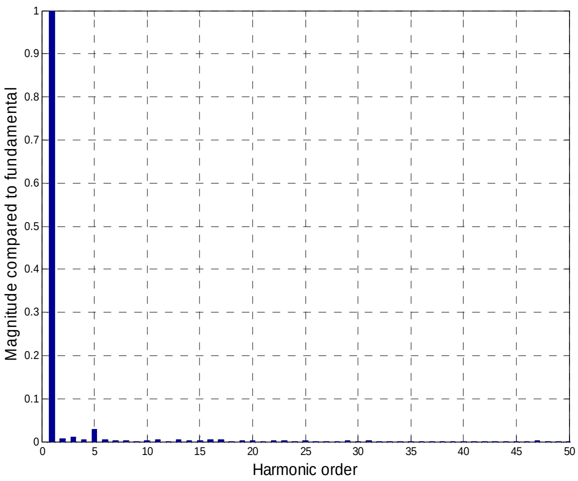


Fig. 11 Spectrum of source current with APF with ANN controller (THD=3.96%)

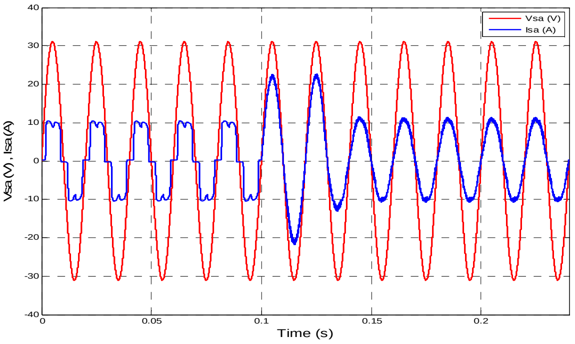


Fig. 12 Current and voltage source before and after compensation with ANN controller (vsa= Vsa/10)

Using the proposed SAF system controlled ANNs controller, we can conclude that the source current after compensation is practically sinusoidal and in phase with the corresponding source voltage. The SAF start the compensation process instantly when it is connected to the non-linear load. The system passes through transient period of 0.04s necessary to attain the steady state of the source current and to stabilize the dc voltage to its reference Udc-ref=800V. The source current THD is significantly reduced from 27.74% to 3.96% in conformity with IEEE standard Norms.

B) Simulation results with Fuzzy current controller

The load current, the injected current and the DC voltage across capacitor before and after shunt active filter operation are shown in Figure 13. Figure 14 shows the harmonic spectrum of the source current after compensation. Finally, the source current and the corresponding source voltage are presented simultaneously in Figure 15.

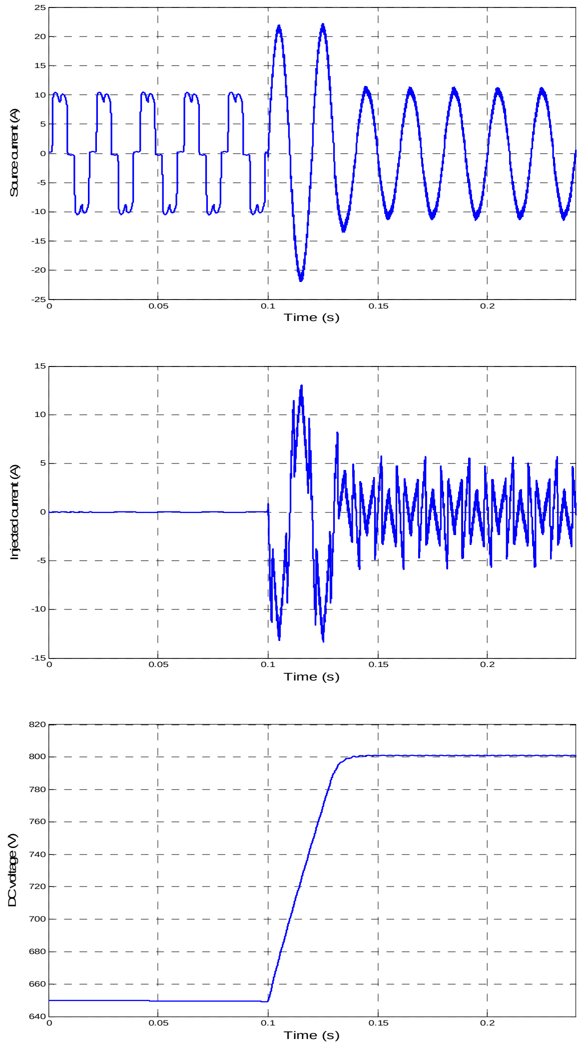


Fig. 13 Line current, injected current and DC voltage before and after compensation using Fuzzy current controller

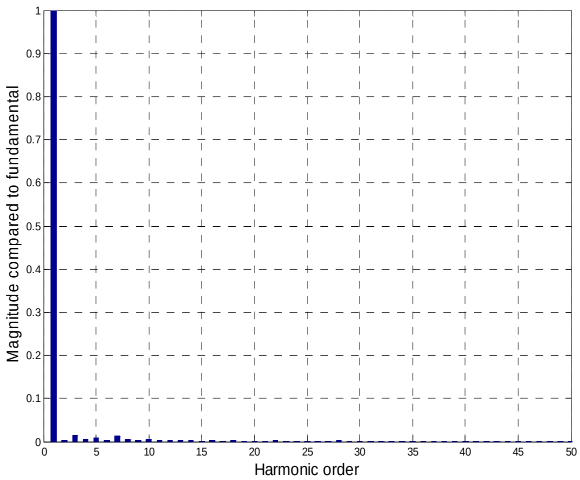


Fig. 14: Spectrum of source current after compensation with Fuzzy controller (THD=1.62%)

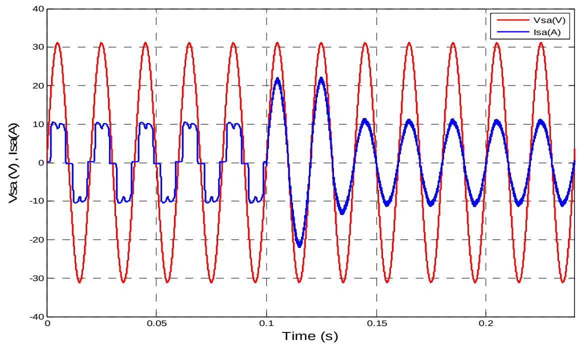


Fig. 15 Current and voltage source before and after compensation with fuzzy controller (vsa= Vsa/10)

By visualizing Figures 12 and 15, we can conclude the successful simulation of the harmonic currents compensation using the two proposed intelligent current controllers. The performances of the three-level shunt active filter based on FLC controller in terms of eliminating harmonics is better than ANN controller. In the two cases, the THD is widely reduced from 27.74% to 3.96% for ANN and to 1.62% for FLC controller. The control strategy based on synchronous current detection method permits a good extraction of reference currents compensation. The PI Controller ensures that the dc voltage across capacitor is maintained constant and equal to reference vale ($U_{dc\text{-}ref}$=800V). The steady state of the source current is obtained after 0.03 sec in the two cases. Figures 12 and 15 shows that the source current after compensation is sinusoidal and in phase with the corresponding source voltage for the two controllers. The THD values obtained respect widely the IEEE standards Norms (THD $\leq$5%).

VI. Conclusion

A three-phase three-level shunt active filter with neutral-point diode clamped topology using intelligent current controllers is proposed to suppress current harmonics. The numerical simulation is performed using MATLAB-Simulink and SimPowerSystem Toolbox. For the two configurations synchronous current detection method strategy is adopted to calculate reference signals, it's concise and requires less computational efforts than many others method control. The current source before compensation is widely distorted and rich on harmonics. After compensation, the harmonic spectrum shows that the THD is widely reduced for the two controllers in conformity with IEEE Norms (THD<=5%) but the ANNs is more efficiency than fuzzy systems. The DC voltage controller ensures that the voltage across capacitors is maintained constant with fast dynamic response in case of load current variation. The current source after compensation is sinusoidal and in phase with the line voltage source with reduced THD vale.

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Three-level (NPC) Series Active Power Filter Performances based on Instantaneous Reactive Power Strategy using Fuzzy Techniques for Harmonic Voltage Disturbances Compensation

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***Abstract* –This paper presents a three-phase three-level (NPC) series active power filter based on instantaneous reactive power strategy to compensate harmonic voltage disturbances for critical loads. The conventional configuration is based on the two-level voltage source inverter with classical controllers requiring a complex and a complicated mathematical model. In order to overcome these drawbacks and improve the series APF performance there is a great tendency to use multilevel converters and intelligent controllers. Today three-level inverter topology and fuzzy logic controller are successfully employed in various industrial applications; in order to get benefits of their advantages a new control scheme for series active power filter is proposed in this paper. The fuzzy voltage controller is designed to improve compensation capability of series active power filter by adjusting the voltage error using a fuzzy rule. The control strategy use instantaneous reactive power theory. The simulation is performed using MATLAB-Simulink and SimPowerSystem Block Set Toolbox. The obtained results show that the proposed Series AF compensate perfectly harmonics voltage disturbances.**

Keywords –Three-level (NPC) series active power filter, Fuzzy logic control, Harmonics voltage compensation, instantaneous reactive power strategy

I. Introduction

With the continuous proliferation of non linear loads, harmonic pollution is being considered as one of the major problems that degrade the power quality. Active power filters have been proposed as an interesting and high performance solution to improve the power quality [1]. Shunt active power filter is generally used to compensate current harmonics. Series active power filter is one of the control devices that feed modern industry with high quality power supply [2], it is used to compensate all types of voltage perturbations, such as voltage unbalances, sags, harmonics and voltage swells, these perturbations have harmful effects on the electric equipments [3],[16].

The series active power filter is inserted in series between the load and the source voltage. Three single phase transformers are used to perform the series connection. The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [4,5], to improve the Series APF performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic controllers. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. The fuzzy control does not need an accurate mathematical model of a plant. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. This control technique relies on the human capability to understand the system's behaviour and is based on qualitative control rules. Thus, control design is simple since it is only based on if....then linguistic rules [6],[7],[8].

The investigation in this paper concentrates on the fuzzy control approaches for the three-phase series APF based on three-level (NPC) inverter to compensate particularly harmonic voltage disturbances using instantaneous reactive power theory control strategy [9]. The performances of the proposed series active power filter are evaluated using Matlab-Simulink software and SimPowerSystem Toolbox.

II. Series active power filter

The circuit configuration of the three-level (NPC) series active power filter is shown in Fig. 1. The Series AF is inserted between the perturbed voltage source and a protected load, it is composed of three phase voltage source converter, $L_{sf}C_{sf}$ filter to suppress switching ripples and series transformers which inject the compensating voltage to the line [10].

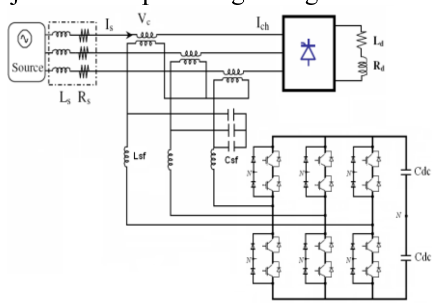


Fig. 1 Three-level (NPC) Series active power filter

III. Control strategy

The proposed series active filter is adopted to compensate voltage harmonics. The control strategy used for extracting the reference voltages of series active power filter is based on the p-q theory described in [11],[12],[13].

We assume that the three-phase voltage source in the grid is symmetric and distorted:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t - \frac{2\pi}{3}) + \theta_n \right] \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t + \frac{2\pi}{3}) + \theta_n \right] \end{bmatrix} \quad (1)$$

Un and θn are respectively the rms voltage and initial phase angle, n is the harmonic order.
When n=1, it means three-phase fundamental voltage source:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sqrt{2} U_1 \sin(\omega t + \theta_1) \\ \sqrt{2} U_1 \sin\left[(\omega t - \frac{2\pi}{3}) + \theta_1 \right] \\ \sqrt{2} U_1 \sin\left[(\omega t + \frac{2\pi}{3}) + \theta_1 \right] \end{bmatrix} \quad (2)$$

Equation (1) is transformed into (α–β) reference frame:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = C_{32} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \sqrt{3} \begin{bmatrix} \sum_{n=1}^{\infty} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \mp U_n \sin(n\omega t + \theta_n) \end{bmatrix} \quad (3)$$

Where:

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (4)$$

Three-phase positive fundamental current template is constructed:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (5)$$

Equation (5) is transformed to (α–β) reference frame:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t \end{bmatrix} \quad (6)$$

According to the instantaneous reactive power theory [11], then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

Where DC and AC components are included:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \quad (8)$$

P and q are passed through low pass filter (LPF) and DC component are got:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \sqrt{3} \begin{bmatrix} U_1 \cos(\theta_1) \\ U_1 \sin(\theta_1) \end{bmatrix} \quad (9)$$

According to (7), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \quad (10)$$

As for DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} u_{\alpha f} & u_{\beta f} \\ u_{\beta f} & -u_{\alpha f} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} \quad (11)$$

The fundamental voltages in (α–β) reference frame are:

$$\begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (12)$$

The three-phase fundamental voltage is:

$$\begin{bmatrix} U_{af} \\ U_{bf} \\ U_{cf} \end{bmatrix} = C_{23} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \sqrt{2} U_1 \begin{bmatrix} \sin(\omega t + \theta_1) \\ \sin(\omega t + \theta_1 - \frac{2\pi}{3}) \\ \sin(\omega t + \theta_1 + \frac{2\pi}{3}) \end{bmatrix} \quad (13)$$

Where:

$$C\,23 = \begin{bmatrix} 1 & 0 \\ -1/2 & \frac{\sqrt{3}}{2} \\ -1/2 & \frac{\sqrt{3}}{2} \end{bmatrix} \quad (14)$$

The block diagram of the harmonic voltage identification based on (p-q) theory is presented in Fig.2.

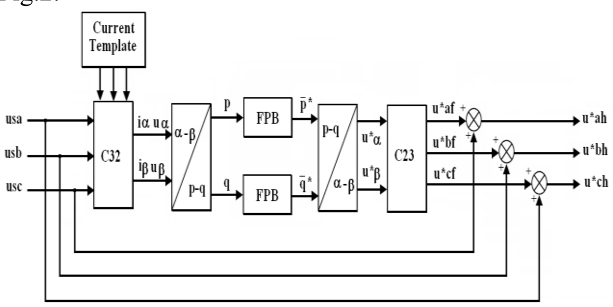


Fig. 2 Block diagram of voltages reference identification

IV. Fuzzy logic control

Fuzzy logic controllers (FLCs) have been interest a good alternative in more power electronics application. Their advantages are robustness, easy implementation and accept non-linearity [05],[14]. To benefit of these advantages a simple fuzzy logic voltage controller is proposed to control the Series APF.

The fuzzy voltage controller proposed in this paper is designed to improve compensation capability of APF by adjusting the voltage error using fuzzy rules. The desired inverter switching signals are determined according the error between the compensate voltages and reference voltages. In this case, the fuzzy logic voltage controller has two inputs, error e and change of error de and one output s. To convert it into linguistic variable, we use seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large). The membership functions used in fuzzification and defuzzification are shown in Fig. 3.

The fuzzy controller for every phase is characterized for the following:

- Seven fuzzy sets for each input,
- Seven fuzzy sets for output,
- Triangular and trapezoidal membership function for the inputs and output,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.

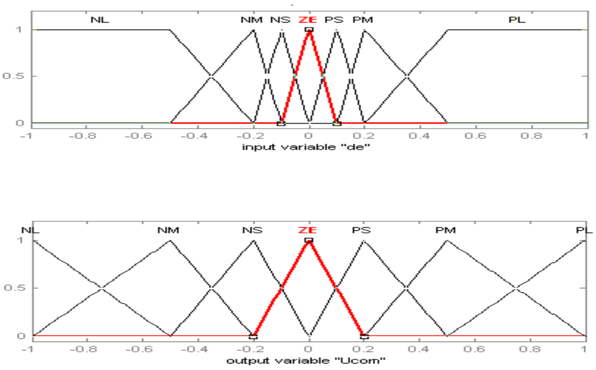


Fig. 3 Inputs and output membership function

The fuzzy rules are given by Table (1).

e de/dt	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	EZ
NM	NL	NM	NM	NS	NS	EZ	PS
NS	NM	NM	NS	NS	EZ	PS	PS
ZE	NM	NS	NS	EZ	PS	PS	PM
PS	NS	NS	EZ	PS	PS	PM	PM
PM	NS	EZ	PS	PS	PM	PM	PL
PL	EZ	PS	PS	PM	PM	PL	PL

TABLE I Fuzzy rules

The generation process of switching signals is given by Fig.4.

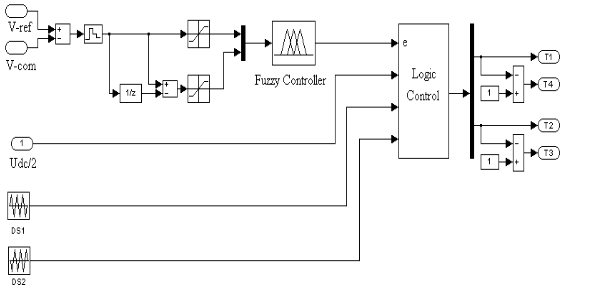


Fig. 4 Fuzzy controller

The controller calculates the difference between the injected voltage and the reference voltage that determines the error voltage, this error voltage pass through fuzzy controller. The fuzzy voltage error is compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses [15].

V. Model and Simulation Results

The block diagram of the proposed three-level (NPC) series active power filter based on fuzzy logic voltage controller is shown in Figure (5).

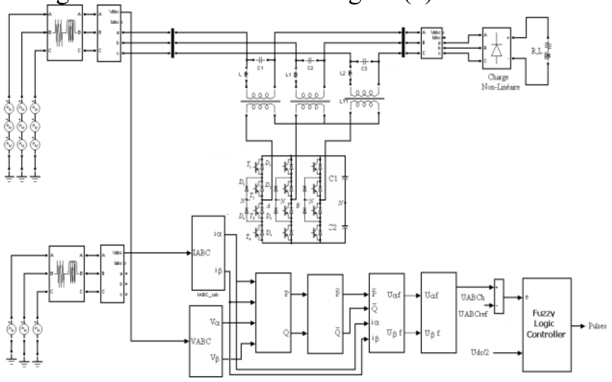
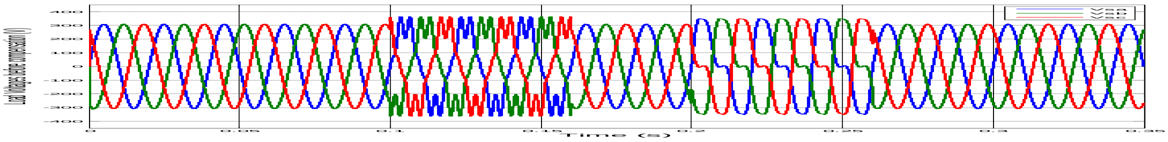


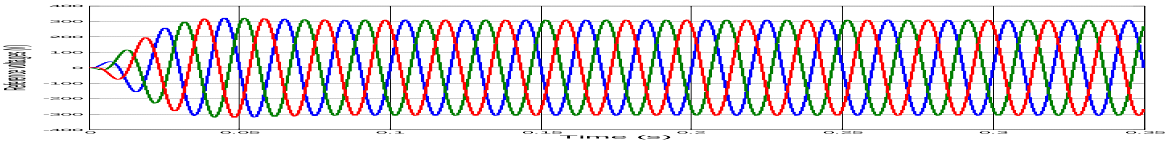
Fig. 5 Series active power filter based on three-level (NPC) inverter using fuzzy controller

The purpose of the simulation is to show the effectiveness of the proposed series active power filter using fuzzy logic controller to compensate a several voltage harmonics introduced voluntary in the power grid. In the starts, we suppose that the three phase voltages are balanced and non-distorted. The first voltage harmonic disturbances is rich on 5 and 7 component harmonics, it is introduced voluntarily at t1=0.1sec to t2=0.16sec. Between t2=0.16 sec and t3=0.2sec, the system is again at normal working condition. The second harmonic voltages disturbances is rich on 2, 4 and 5 component harmonics, it is introduced between t3=0.2sec and t4=0.26sec.

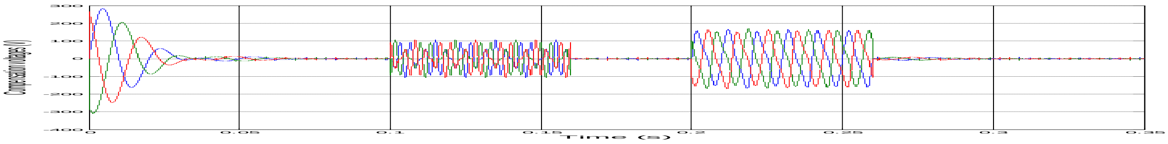
The series APF starts compensating voltage harmonics instantly. Fig. 6 shows the load voltage before series compensation, reference voltage, injected voltage delivered by series APF and the load voltage after compensation. The harmonic spectrum of the load voltage before and after compensation is shown respectively in Fig.7 to Fig.10.



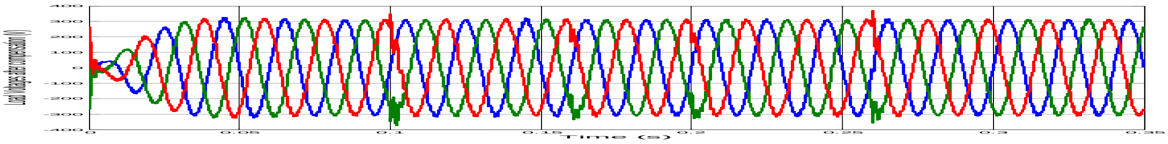
(a) Load voltage before compensation



(b) Reference voltages



(c) Compensation voltages



(d) Load voltage after compensation

Fig.6 Load voltage before compensation, reference voltages, injected voltages and load voltages after compensation

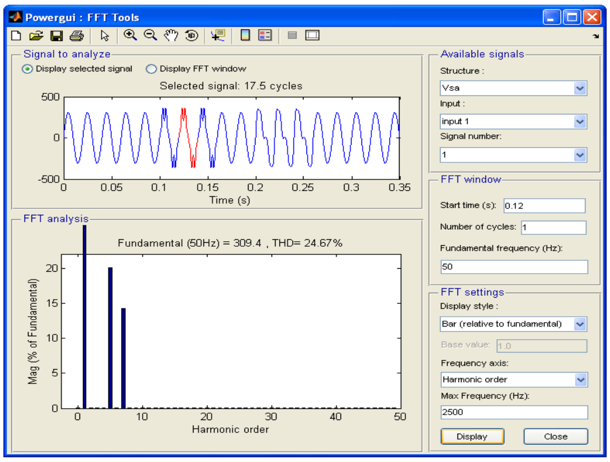


Fig. 7 Load voltage harmonic spectrum without Series AF (THDv=24.67%)

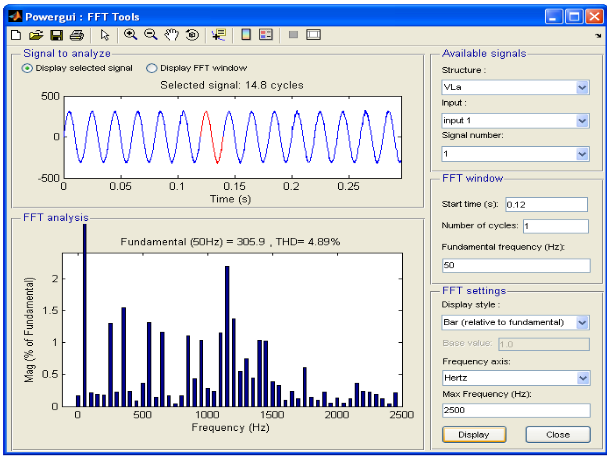


Fig. 8 Load voltage harmonic spectrum with Series AF using fuzzy controller (THDv=4.89%)

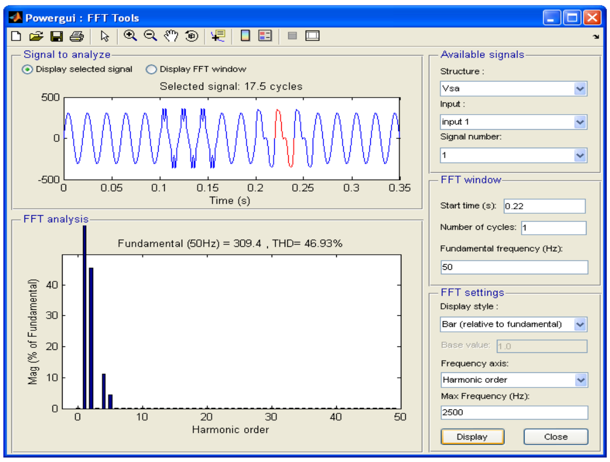


Fig. 9 Load voltage harmonic spectrum without Series AF (THDv=46.93%)

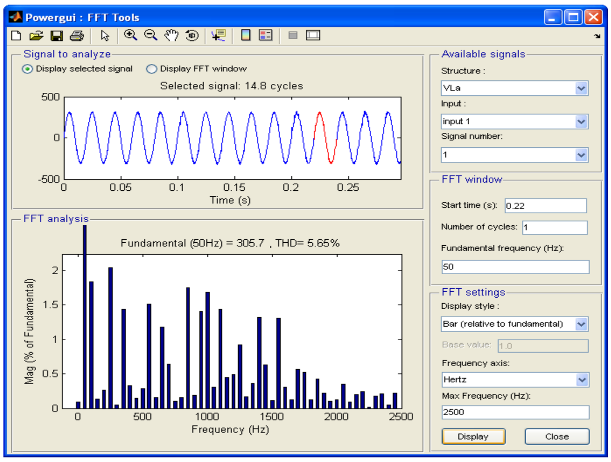


Fig. 10 Load voltage harmonic spectrum with Series AF using fuzzy controller (THDv=5.65%)

The performance of the proposed Series AF system is tested under two distorted voltage supply. The simulation result shows that the load voltage before compensation is highly distorted; its THDv is equal to 24.67% for the first harmonics type and 46.93% for the second one. After compensation the THDv is widely reduced to 4.89% and 5.65% with fast dynamic responses. The simulation results obtained using MATLAB-Simulink and SimPowerSystem show the effectiveness of the proposed series APF based on fuzzy voltage controller to ensure a pure sinusoidal voltage for sensible or critical loads at distorted supply network. However, the current source is highly distorted and rich on harmonics. To eliminate this drawback, the future research work will be focused on current source compensation using hybrid series active filter configuration or Unified Power Quality Conditioner system.

VI. Conclusion

To improve the power quality and reduce the source voltage harmonics delivered to sensible or critical loads, a new series active power filter configuration using fuzzy logic voltage controller based on three-level (NPC) inverter has been proposed in this paper. The control strategy used to determine compensation voltages is the PQ theory. It is proved that the proposed series active filter compensates effectively the voltage harmonics with fast dynamic responses, the voltage delivered to critical or sensible loads is practically sinusoidal and without harmonics. The solution proposed in this article can be very interesting to equip power sensible loads especially if the voltage source is highly distorted. The MATLAB-Simulink results show that the load voltage harmonics is significantly reduced from 24.67% to 4.89% and from 46.93% to 5.65% in conformity with the IEEE standard Norms.

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Power Energy Quality Improvement using Shunt Active Power Filter based on Fuzzy Control Techniques under Non-Ideal Voltage Conditions

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Keywords

Shunt active power filter, Fuzzy control techniques, Synchronous reference detection method, Harmonic currents compensation, Non ideal voltages conditions.

Abstract

This paper presents a three-phase shunt active filter based on fuzzy control techniques to compensate current harmonics under non ideal voltage conditions. The control strategy adopted use synchronous reference frame detection method; it is generally used if the source voltage is unbalanced or distorted. Today, fuzzy logic controllers are used in various power electronics applications; their advantages are simple design, no need mathematical model, based on linguistic description and are more robust than conventional controllers. To compensate the inverter losses and maintain the dc voltage capacitor constant a proportional integral controller is used. The simulation model is developed and performed using MATLAB-Simulink and SimPowerSystem Toolbox. The simulation results obtained show the effectiveness of the proposed Shunt APF system under non ideal voltage conditions.

I. Introduction

A large part of total electrical energy, produced in the world, supplies different types of non-linear loads. The loads such as variable frequency drives and electronic ballasts draw current, which does not resemble the grid sinusoidal voltage. This load is said to be non-linear and typically is composed of odd order currents, which are expressed as multiples of the fundamental frequency. The harmonic current cannot contribute to active power and need to be eliminated to enhance the power quality [1]. Active Power Filter (APF) is the popular solution used to eliminate the undesired current components by injection of compensation currents in opposition to them [2],[3]. The performance of any active filter mainly depends on the reference current generation strategy, control techniques, converter topology, etc…
Several papers studied and compared the performances of different reference current generation strategies under balanced, sinusoidal, unbalanced or distorted voltage conditions [3],[4]. In all of them, the P-Q strategy and SRF provide similar performances. But when, the active filter work under distorted and unbalanced AC voltages (real conditions) the best results are obtained with the synchronous reference frame method. However, the SRF theory requires a phase locked loop (PLL) which increases the complexity of the control system.

In recent years, fuzzy logic controllers have generated a great deal of interest in different applications [5],[6]. Their advantages are robustness, no need mathematical model and accept non-linearity. This paper is focused on the compensation current harmonic capability using three-phase shunt active filter based on fuzzy logic current controller under non ideal voltages conditions. The performances of the proposed shunt active filter are evaluated through computer simulations for transient and steady-state conditions using Matlab-Simulink and SimPower System Block-Set Toolbox. The obtained results show the effectiveness and the robustness of the proposed SAPF system under different voltage conditions.

II. Shunt active power filter

The basic block diagram including non linear load compensation principle of a shunt active power filter is shown in Fig. 1. It is controlled to compensate harmonic currents generated by the non-linear load and makes the source current in phase with the source voltage. After compensation the source current at the coupling point of the shunt APF is sinusoidal and without harmonics [7],[8].

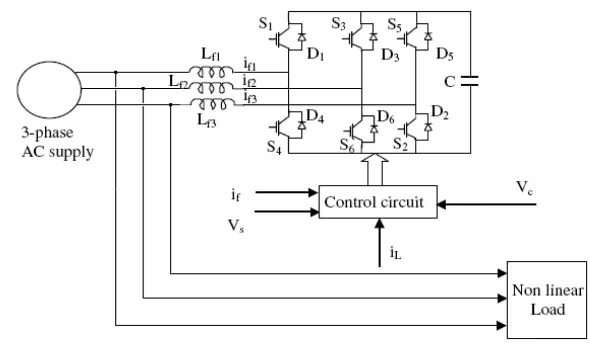


Fig. 1 Shunt active filter

III. Synchronous reference frame detection method

The control strategy to compensate harmonic currents used in this work is based on the synchronous reference frame detection method. The principle of this technique is described below [9]. The three phase currents i_a, i_b and i_c are transformed from three phase (abc) reference frame to two phase's (α-β) stationary reference frame currents i_α and i_β using:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

Using a PLL (Phase Locked Loop), we can generate $\cos(\hat{\theta})$ and $\sin(\hat{\theta})$ from the phase voltage source v_{sa}, v_{sb} and v_{sc}. The currents expression i_α and i_β in (d-q) reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\hat{\theta}) & -\cos(\hat{\theta}) \\ \cos(\hat{\theta}) & \sin(\hat{\theta}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

These components can then be expressed as the sum of a DC component and AC component

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d & + & \tilde{i}_d \\ \bar{i}_q & + & \tilde{i}_q \end{bmatrix} \quad (3)$$

With $\bar{i}_d, \bar{i}_q$ are the continuous components of id and iq, and $\tilde{i}_d$, $\tilde{i}_q$ are the alternative components of id and iq. From equation (2), we can express the current components along the axes (αβ) by:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d \\ \bar{i}_q \end{bmatrix} + \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \tilde{i}_d + i_{cd} \\ i_q \end{bmatrix} \tag{6}$$

The reference currents in the (abc) frame are given by:

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \tag{7}$$

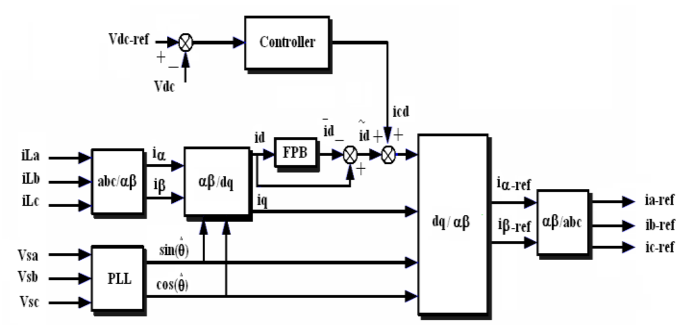


Fig. 2 Synchronous reference frame detection method

IV. DC voltage control

The regulation loop consists of the comparison of the measured voltage with the reference voltage, admitting that the function of the system to be controlled is given by [10],[11]:

$$\frac{V_s{}^2}{(U_{dc-ref}.C_{dc}.s)} \tag{8}$$

The closed loop transfer function using a PI regulator is given by:

$$\frac{U_{dc}}{U_{dc-ref}} = \frac{(K_p + K_i/s).(V_s{}^2/(V_{dc-ref}.C_{dc}.s))}{1+(K_p + K_i/s).(V_s{}^2/(V_{dc-ref}.C_{dc}.s))} \tag{9}$$

The development of this equation gives:

$$\frac{U_{dc}}{U_{dc-ref}} = \frac{\frac{K_p V_s{}^2}{V_{dc-ref}.C_{dc}}.s + \frac{K_i}{V_{dc-ref}.C_{dc}}}{s^2 + \frac{K_p V_s{}^2}{V_{dc-ref}.C_{dc}}.s + \frac{K_i V_s{}^2}{V_{dc-ref}.C_{dc}}} \tag{10}$$

A second order characteristic equation of the closed loop system is deduced:

$$s^2 + 2\xi\omega_n s + \omega_n{}^2 = 0 \tag{11}$$

Where:

$$\omega_n = \sqrt{\frac{K_i V_s^2}{U_{dc-ref}.C_{dc}}} \quad , \qquad \xi = \frac{K_p V_s}{2\sqrt{K_i .U_{dc-ref}.C_{dc}}} \tag{12}$$

From (11) the proportional and integrator coefficient K_p , K_i of the controller can be deduced:

$$K_p = \frac{2.\xi.K_i}{\omega_n} \quad , \qquad K_i = \frac{\omega_n^2 .U_{dc-ref}.C_{dc}}{V_s^2} \tag{13}$$

The expression of the current I_{cd} to compensate the inverter losses and maintain the constant dc-link voltage is given by:

$$I_{cd} = K_p .\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \tag{14}$$

To obtain optimal dynamic performance for the system, the value of the damping ration ξ must be equal a 0.707.

V. Fuzzy logic control

Among the various current control techniques, hysteresis current control is the most extensively used technique. It is easy to realize with high accuracy and fast response. In the hysteresis control technique the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteretic controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. The proposed fuzzy logic current controller provides fixed switching frequency and lower ripple content. The advantages of fuzzy controllers are more robust than conventional controllers, no need an accurate mathematical model and essentially accept non-linearity [10],[11]. Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action [12], [13]. The desired inverter switching signals of the shunt active filter are determined according the error between the compensate currents and reference currents. A fuzzy controller is designed to improve compensation capability of APF by adjusting the current error using a fuzzy rule. In this case, the fuzzy logic current controller has two inputs, named error e and change of error de and one output named s. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig. 3 shows the membership functions used in fuzzification.

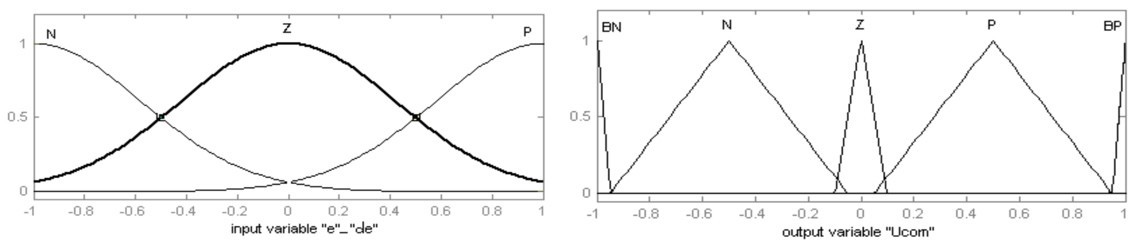


Fig. 3 Membership function for the inputs variables

The fuzzy controller for every phase is characterized for the following:

- Three fuzzy sets for each input,
- Five fuzzy sets for each output,
- Triangular and trapezoidal membership functions,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.

The linguistic rules for the fuzzy current controller are as follows:

1. If error is Negative and error rate is Negative Then output is Big Negative,
2. If error is Zero and error rate is Negative Then output is Positive,
3. If error is Positive and error rate is Negative Then output is Big Positive,
4. If error is Negative and error rate is Negative Then output in Big Negative,
5. If error is Zero and error rate is Zero Then output is Zero,
6. If error is Positive and error rate is Zero Then output is Big Positive,
7. If error is Negative and error rate is Positive Big Then output is Big Negative,
8. If error is Zero and error rate is Positive Then output is Negative,
9. If error is Positive and error rate is Positive Then output is Big Positive.

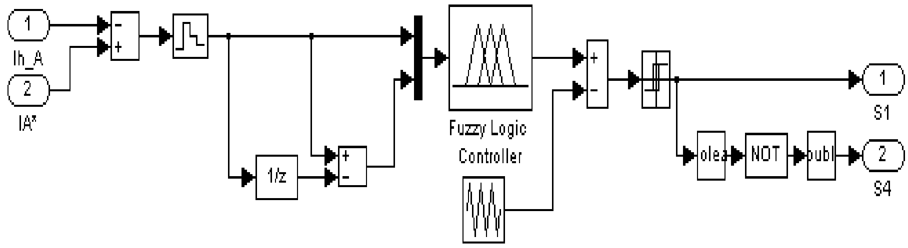


Fig. 4 Fuzzy logic inverter switching signals

VI. Simulation results and discussion

Figure (5) shows the block diagram of the shunt active filter based on fuzzy current controller developed using Matlab-Simulink and SimPowerSystem Toolbox.

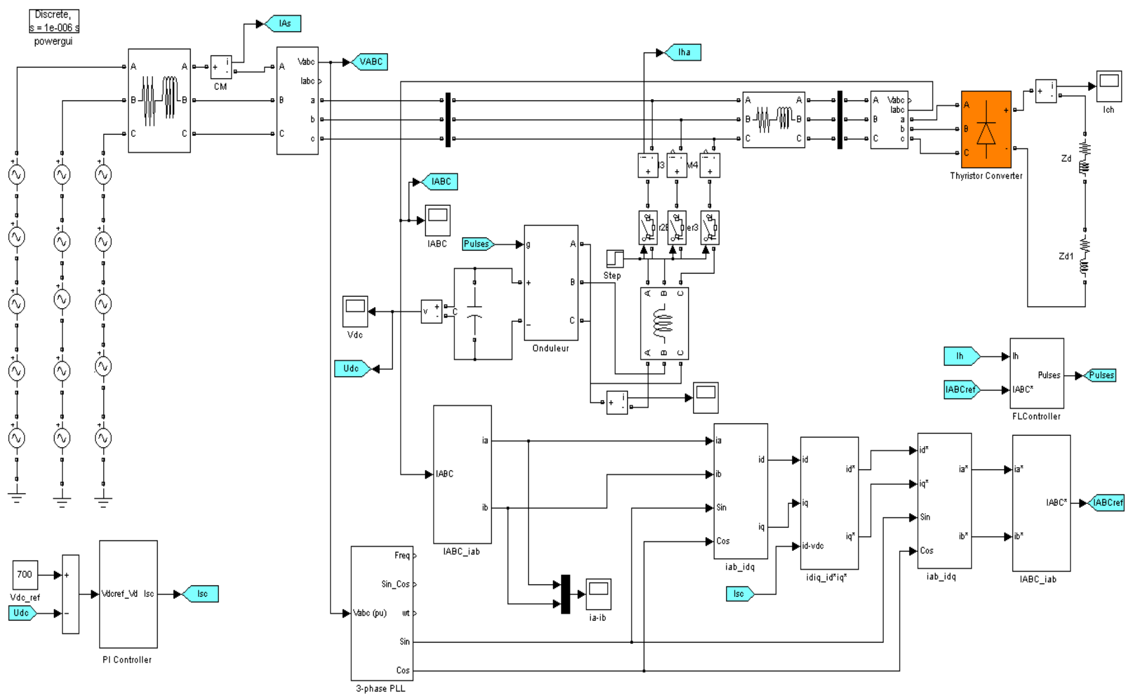
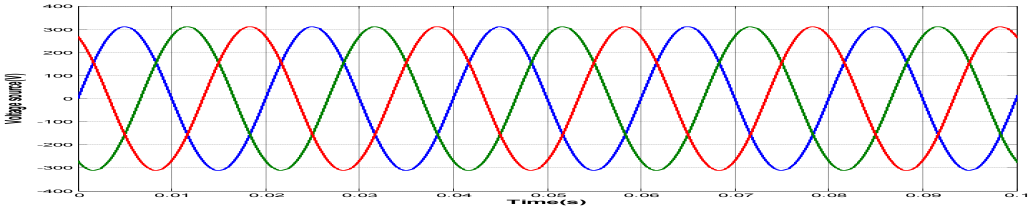


Fig. 5 Matlab-Simulink block diagram of the Shunt APF based on Fuzzy logic controller

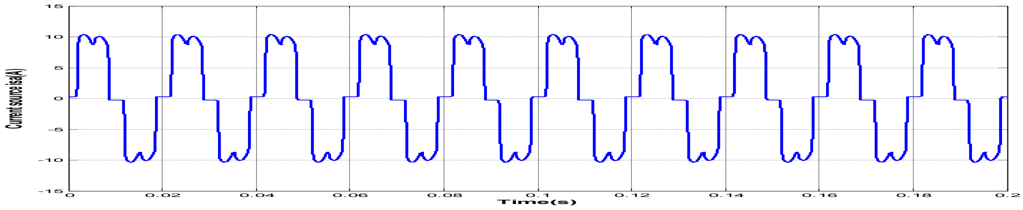
The purpose of the simulation is to show the performances of the proposed shunt active power filter operation using a fuzzy controller to reducing the harmonic currents produced on the load side under non ideal voltages conditions. The model parameters used for simulation are: Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_{ch} =48.6Ω, Inductance L_{ch}=40mH, DC Voltage U_{dc} =700V, Capacitance C_{dc}=3000μF, Resistor R_c=0.27m Ω, Inductance L_c=0.8mH.

VI.1 Ideal voltage conditions case

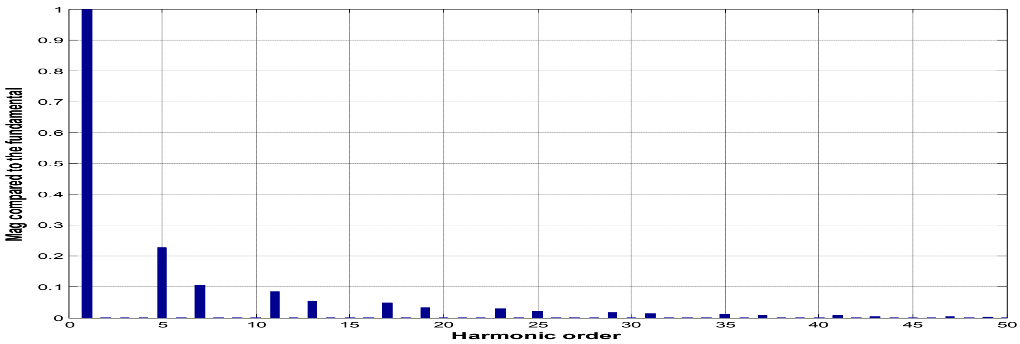
The three-phase voltages source are balanced and do not contain harmonic components, Fig. 6 (a), Fig. 6(b) and Fig. 6 (c) shows the voltage source, line current and its spectrum before compensation. The line current and its spectrum after compensation are presented in Fig. 6 (d) and Fig. 6 (e). Fig. 6 (f) show the current and voltage source, finally Fig. 6 (g) shows the dc voltage.



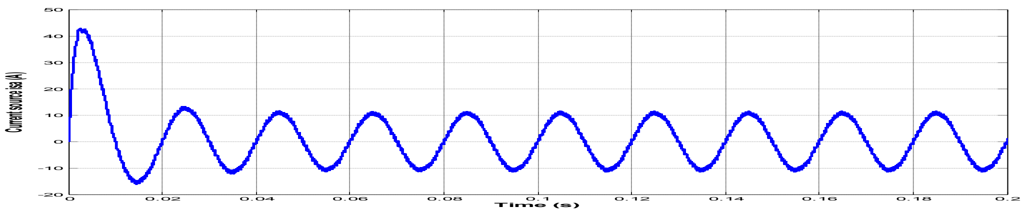
(A)-Supply voltage



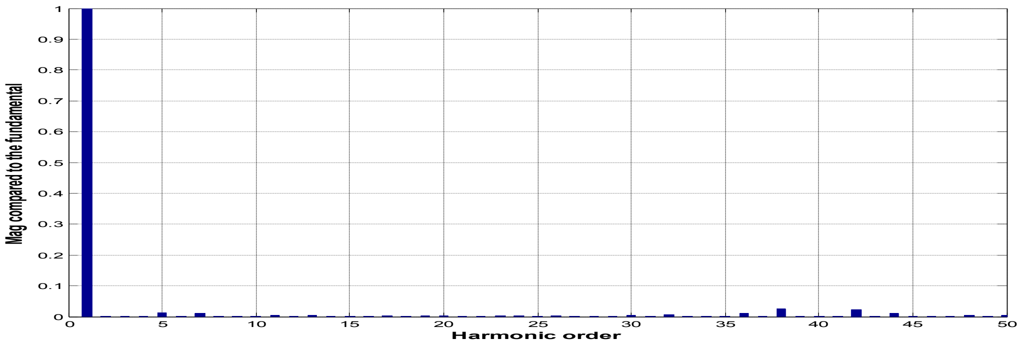
(B)-Source current before compensation



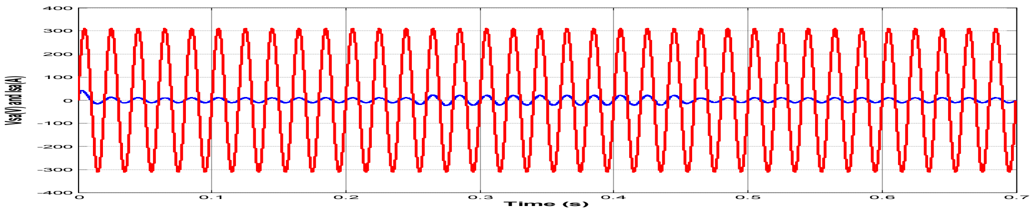
(C)-Source current Spectrum THD 28.16%



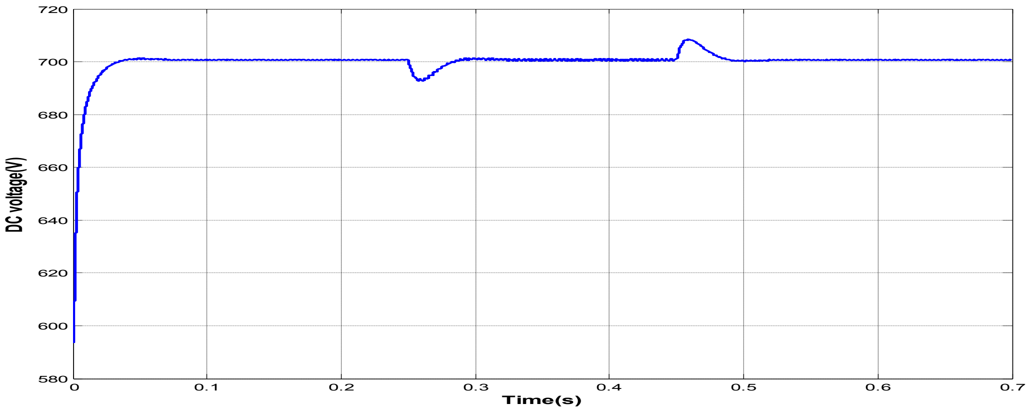
(D)-Source current after compensation



(E)-Source current spectrum THD 2.28%



(F)-Current and source voltage



(G)-DC voltage capacitor

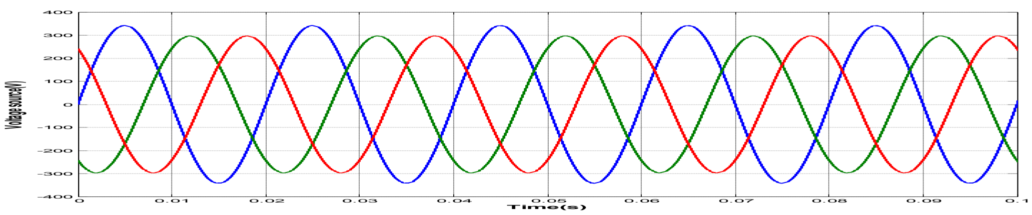
Fig. 6 Ideal voltages conditions

VI.2 Unbalanced voltage conditions case

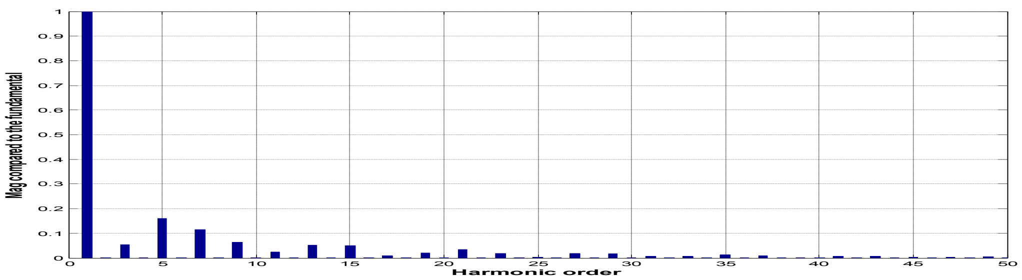
The three phase voltages sources are unbalanced and do not contain harmonic components; their expressions are given by (15):

$$
\begin{aligned}
v_{sa} &= 311\sin(\omega t) + 31\sin(\omega t) \\
v_{sb} &= 311\sin(\omega t - \frac{2\pi}{3}) + 31\sin(\omega t + \frac{2\pi}{3}) \\
v_{sc} &= 311\sin(\omega t + \frac{2\pi}{3}) + 31\sin(\omega t - \frac{2\pi}{3})
\end{aligned} \qquad (15)
$$

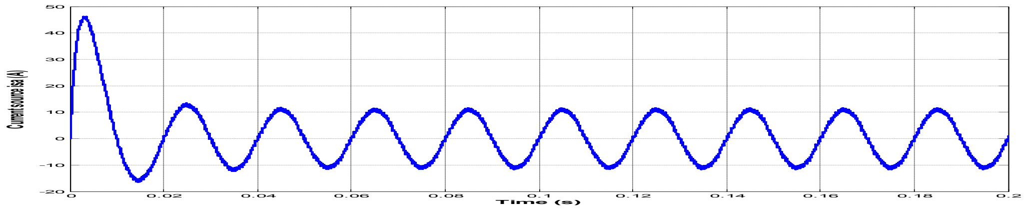
Fig. 7 (a) and Fig.7 (b) shows the unbalanced voltage source and the line current source spectrum before compensation. The line current and its spectrum after compensation are presented in Fig. 7 (c) and Fig. 7 (d). Finally the dc voltage is presented in Fig. 7 (e).



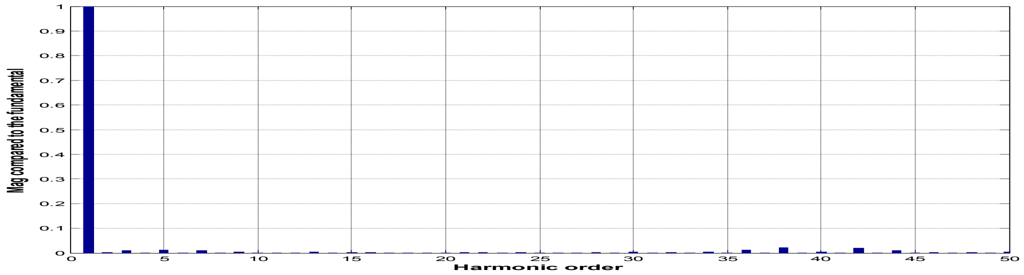
(A)-Unbalanced voltage



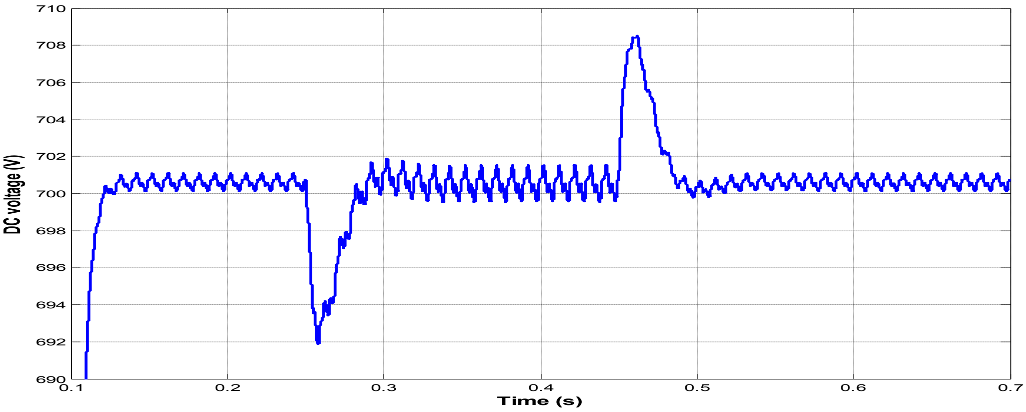
(B)-Source current Spectrum THD 27.50%



(C)-Source current after compensation



(D)-Source current Spectrum THD 4.96%



(E)-DC voltage capacitor

Fig. 7 Unbalanced voltages conditions

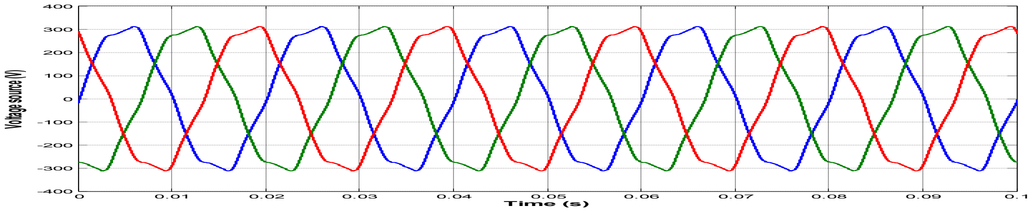
VI.3 Balanced-distorted voltage conditions case

When the three phase voltages are balanced and distorted, mains voltages contain harmonic voltage components except fundamental component. The expression of the balanced-distorted voltages source used in this work contains the 5th harmonic component and also the 3rd, 7th, 11th harmonic component. For this case, the balanced distorted three phase mains voltages are expressed as below:

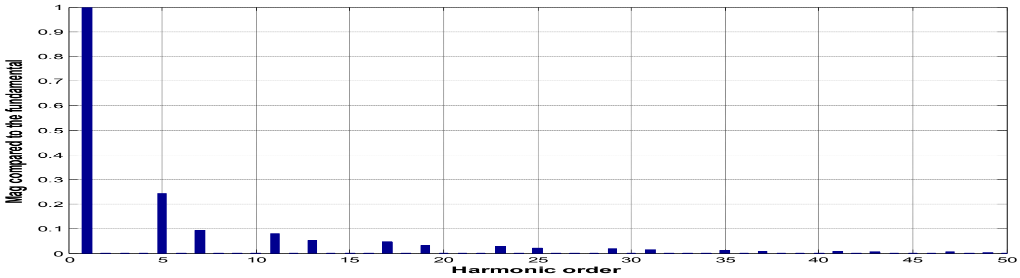
$$v_{sa} = 311\sin(\omega t) + 3.7\sin(3\omega t) + 18.6\sin(5\omega t + \frac{4\pi}{3})$$
$$+4.5\sin(7\omega t) + 3.1\sin(11\omega t + \frac{4\pi}{3})$$
$$v_{sb} = 311\sin(\omega t + \frac{4\pi}{3}) + 3.7\sin(3\omega t) + 18.6\sin(5\omega t)$$
$$+4.5\sin(7\omega t + \frac{4\pi}{3}) + 3.1\sin(11\omega t)$$
$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 3.7\sin(3\omega t) + 18.6\sin(5\omega t + \frac{2\pi}{3})$$
$$+4.5\sin(7\omega t + \frac{2\pi}{3}) + 3.1\sin(11\omega t + \frac{2\pi}{3})$$

Fig. 8(a) and Fig. 8(b) shows the balanced-distorted voltage source and the line source current spectrum before compensation. The line current and its spectrum after compensation are presented in

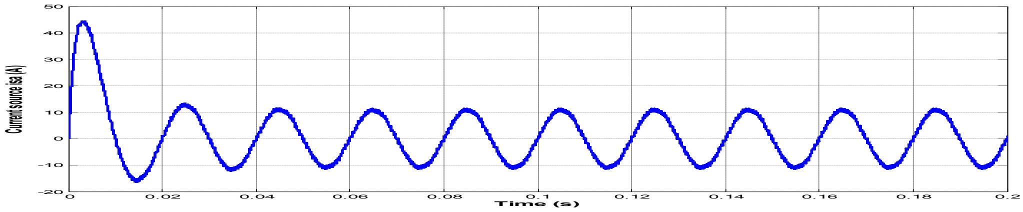
Fig. 8(c) and Fig. 8(d). Finally the dc voltage is presented in Fig. 8 (e).



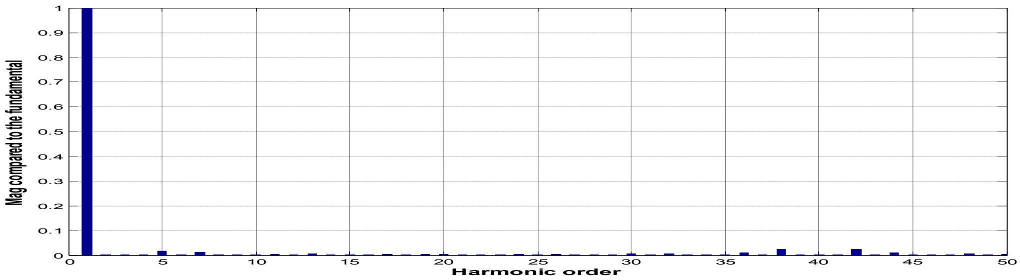
(A)-Balanced-distorted voltage



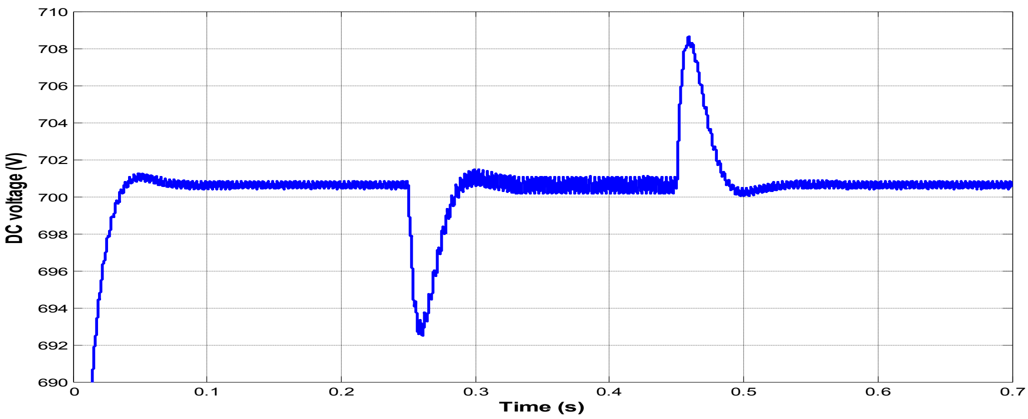
(B)-Source current Spectrum THD 28.75%



(C)-Source current after compensation



(D)-Source current Spectrum THD 4.62%



(E)-DC voltage capacitor

Fig. 8 Balanced and distorted voltages source

By inspecting Fig. 6(b), Fig. 7(b), Fig. 8(b) of the source current after compensation in all cases, we can see obviously the success in simulating of the harmonic currents compensation using fuzzy logic current controller. The current source is sinusoidal and in phase with voltage source, the power factor is nearly equal to unity. The THDi values obtained in different cases with the proposed controller respect the IEEE standard Norms. The DC voltage capacitor is maintained constant and equal to U_{dc-ref}=700V using a proportional integral controller. The dynamic response is very fast in case of step change in load current. Fig.6(g), Fig.7(g), Fig.8(g) shows that the ripples on DC voltage are more important in unbalanced voltage case than the balanced-distorted voltage case. The minimum of the ripple are obtained in the balanced voltage case.

VII. Conclusion

To improve the power quality and to reduce the current source harmonics, a shunt active power filter configuration using fuzzy logic current controller operating under non ideal voltage conditions has been proposed in this paper. The simulation results show that the source current before compensation is highly distorted and rich on harmonics. After compensation using proposed shunt APF the source current becomes closely sinusoidal and in phase with correspondent source voltage. After compensation, the THDi is widely reduced from 28.16% to 2.28% in ideal voltage case and to 4.96% for distorted voltage case. The ripples on DC voltage in distorted or unbalanced cases are more than the balanced voltage case. The simulation is performed using MATLAB-Simulink and SimPowerSystem Toolbox. The simulations results show the efficiency of the proposed shunt APF in all source voltage cases. The source current after compensation is sinusoidal and in phase with line voltage source for all cases. The current harmonic spectrum respects IEEE-519 standard Norms.

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