Novel Structure for Unbalance, Reactive Power and Harmonic Compensation Based on VFF-RLS and SOGI-FLL in Three Phase Four Wire Power System

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***Abstract*— In this paper a new unbalance, reactive power and load harmonic compensation procedure based on variable forgetting factor-recursive least squares (VFF-RLS) and new phase locked loop is proposed. For this purpose, harmonic component of load current and its positive sequence are estimated with VFF-RLS. Independency on order and amplitude of harmonics, fast dynamic and high accuracy is the bold features of designed estimators. As in the case of load increase/decrease, sag/swell and phase jump in voltage, the optimal compensation is done in less than half a cycle with low THD value. In addition to compensate an infected power network by oscillation frequency, second order general integrator-frequency locked loop (SOGI-FLL) control loop based on wavelet transform (WT) and fuzzy logic controller (FLC) has been proposed. This phase detector can track the reference phase of network in the best manner in the presence of frequency oscillation. Efficiency of the discussed method in a three-phase power system has been validated using both simulations in MATLAB and experimental results.**

Keywords— Distorted power network, Load compensation, SOGI-FLL control loop.

I. INTRODUCTION

As more power electronic converters and other nonlinear loads are applied to power industry, harmonics in power system are also increased [1]. Improper performance of power line equipment, power loss increase and power quality decrease are the main bad effects of these harmonics [2]. As a first solution, passive power filters (PPF) was proposed. The major disadvantage of PPF is its unselective compensation characteristic and probable resonance with harmonic components. So in the case of variable frequency loads such as induction furnaces, PPF may enlarge the harmonic effects and deteriorate the system condition. Next useful approach for harmonic compensation is active power filter (APF). Control algorithms are mostly based on time domain calculations such as instantaneous power theory, synchronous reference frame, or frequency domain such as; Fast Fourier Transform (FFT). The main drawback of both types is experimental implementation limitation on digital processors due to their large and complex computations, resulted in delay and improper performance in different operating conditions of system [3]. Recursive least square is a powerful mathematical tool to online estimation of signal parameters. In RLS method by interring estimated data at n'th sampled time and the measured data of signal at (n+1)'th sampled time, new estimation on n+1 sample time takes place. So the required memory is low and experimental implementation with digital processors would be easier. In order to fast and accurate estimation of parameter in transient and steady state of signal, RLS is structured based on variable forgetting factor which can be called VFF-RLS estimator [4-5].

On the other hand, to estimate main component of load current and it's positive sequence system reference phase should be detected [6-8]. In order to have an accurate and fast phase traction in an infected power network both in polluted voltage and oscillation frequency conditions, SOGI-FLL control loop based on WT and FLC has been proposed. First fundamental component of voltage signal is extracted using FIR filter and IDWT. Then reference phase is achieved using SOGI-FLL based on FLC. In order to verify the proposed control method, both simulation results in MATLAB and experimental results are presented in this research work.

II. PROPOSED CONTROL METHOD

In this method, proposed for three phase four wire system, load currents are used to produce compensating currents. Positive sequence component of load current fundamental component is estimated. Then, by calculating compensating currents, grid side current will be reformed and reactive power will be compensated. This novel method will also omit the load unbalances effect on grid current. Fig. 1 shows the structure of proposed method.

A. Signal Parameter Estimation with VFF-RLS

Recursive least square is a powerful mathematical tool for online estimation of signal parameters. In RLS method we

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consider that the estimation of signal parameters is done till (t)'th sampled time. By interring the measured data of signal at (t+1)'th sampled time, previous estimation is updated based on this data. In other words, there is an online correlation between measured and estimated signal. With every new sample of measured signal, the estimated parameters are updated. By considering the measured signal equal to (1), (2) (estimation equation) and (3) (update equation) fulfill the estimation process [3].

$$y(t) = \Phi^T(t)\theta(t) \tag{1}$$

$$\hat{\theta}(t+1) = \hat{\theta}(t) + P(t+1)\Phi(t+1)[y(t+1) - \Phi^T(t+1)\hat{\theta}(t)] \tag{2}$$

$$P(t+1) = \frac{1}{\lambda(t)}[P(t) - \frac{P(t)\Phi(t+1)\Phi^T(t+1)P(t)}{1+\Phi^T(t+1)P(t)\Phi(t+1)}] \tag{3}$$

$$, 0 < \lambda(t) \leq 1$$

where, θ is estimation parameter vector, ϕ^T is estimation parameters factor or regressors vector, P is covariance matrix and λ is forgetting factor. λ is used to increase convergence speed of RLS method in transient state. In other words, when the signal parameters have no change λ is equal to one and so the estimation has high accuracy. Though, when the signal is transient the λ decreases and so covariance matrix is reset. With resetting covariance matrix, the sampled data in (t+1)'th have more effect in estimation procedure and as a result convergence speed increase. In the other hand the estimation accuracy will reduce. Also when the signal is transient the less λ variation time leads to the more estimation accuracy and speed [10]. In this paper this time is decreased to 0.1 ms by applying unit zone control method to forgetting factor change. VFF is given by (4) [5].

$$\lambda(t) = \lambda_{\min} + (1-\lambda_{\min})2^{-[\rho\alpha^2(t)]} \tag{4}$$

λ_{min} is the minimum value of forgetting factor, ρ is unit zone width controller and α is estimation error, expressed as (5).

$$\alpha(t) = y(t+1) - \Phi^T(t+1)\hat{\theta}(t) \tag{5}$$

1) Load Current Fundamental Component Estimation: Equation (6) illustrates load current Fourier transformation for one of the phases.

$$y(t) = y_{dc} + \sum_{j=1}^{J} (a_j \sin(j\omega t) + b_j \cos(j\omega t)) \tag{6}$$

According to (1), estimation parameter vector and regressors vector can be formed as (7) and (8), respectively.

$$\theta^T(t) = [y_{dc} \quad a_1 \quad b_1 \ldots a_J \quad b_J] \tag{7}$$

$$\Phi^T(t)=[1 \ \sin(\omega t) \ \cos(\omega t) \ \sin(3\omega t) \ \cos(3\omega t) \ldots \ \sin(J\omega t) \ \cos(J\omega t)] \tag{8}$$

Equation (8) illustrates the regressors vector for load current of phase "a". Other phases are shifted 120 and 240 degree respectively. Finally using (2) and (3) estimation parameter vector is calculated for each phase current. Considering load current content, y_{dc} and b_j will equal zero and (9) will be written as below:

$$I_{a1}(t) = a_1 \sin(\omega t) \tag{9}$$

So fundamental component of load current (I_{abc1}) are extracted.

2) Positive Sequence of Load Current Fundamental Component Estimation: Equation (10) can be used to extract symmetric sequences of load current fundamental component.

$$[I_{a1} \quad I_{b1} \quad I_{c1}]^t = T[I_0 \quad I_+ \quad I_-]^t \tag{10}$$

T is symmetric sequences matrix. With the aim of compensating load harmonics, omitting unbalances and producing required reactive power, positive sequence of load current fundamental component is used in order to produce reference signals. To lower the complexity of symmetric sequences estimation and to enhance dynamic of proposed method, zero sequence is subtracted from total load current fundamental component. Zero sequence current is equal to average of fundamental component of estimated load current. Considering (11) as a new form of (1) and using (2) and (3), positive sequence of fundamental component of load current ($I_{abc1,+}$) is estimated.

$$\begin{bmatrix} i_{a1}(t) - I_0(t) \\ i_{b1}(t) - I_0(t) \\ i_{c1}(t) - I_0(t) \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \sin(\omega t) \\ \sin(\omega t - 120) & \sin(\omega t + 120) \\ \sin(\omega t + 120) & \sin(\omega t - 120) \end{bmatrix} \begin{bmatrix} I_+ \\ I_- \end{bmatrix} \tag{11}$$

Finally reference compensating currents (I_{ref}) are produced as Fig. 1.

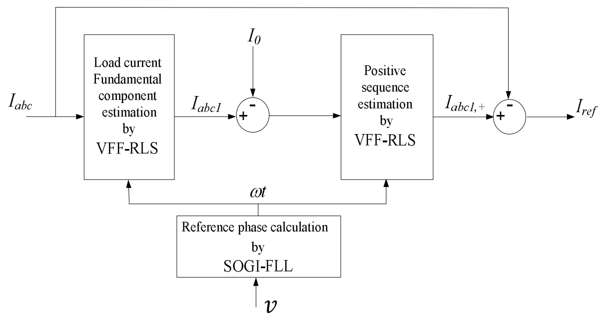

Fig. 1. Novel control structure for compensation purposes

B. *Identify Reference Phase Calculation Using SOGI-FLL Based on FLC and WT*

Considering regressor vector in (8) and (13), to estimate fundamental component of load current, needs to track reference phase of voltage both accurately and fast. Fig. 2 shows the block diagram of the proposed SOGI-FLL. Fig. 3 illustrates bode diagram of SOGI-FLL with constant "k" and different ω'. Fig. 4 is just vice versa. According to this figures with an increase in "k", response time decrease, bandwidth increase and thus sensitivity of SOGI-FLL to input voltage distortion increases. In contrast a reduction of "k", grows response time, lower bandwidth, and thereby reduces sensitivity of SOGI-FLL to input voltage distortion. So if the input voltage signal of SOGI-FLL is distorted, accurate and quick response cannot be yielded [9-11]. In this article by removing harmonic distortion of terminal voltage and extraction of it's fundamental component, voltage distortion in SOGI-FLL input voltage has fallen sharply, resulting in a rapid and accurate response with high "k". f_c is the power system reference frequency ($\omega_c = 2\pi f_c$). For this purpose FIR filter and IDWT analyses in [12] is applied to SOGI-FLL. Since the extracted signal has very low THD and very high accuracy, by selecting high values for "k", reference phase can be tracked very appropriately in both polluted conditions (both voltage harmonic and oscillation frequency).

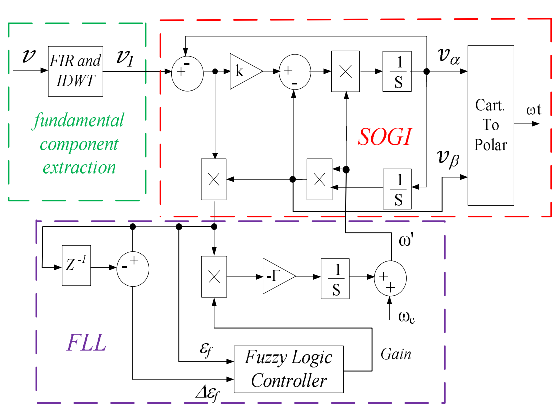

Fig. 2. Block diagram of the proposed SOGI-FLL

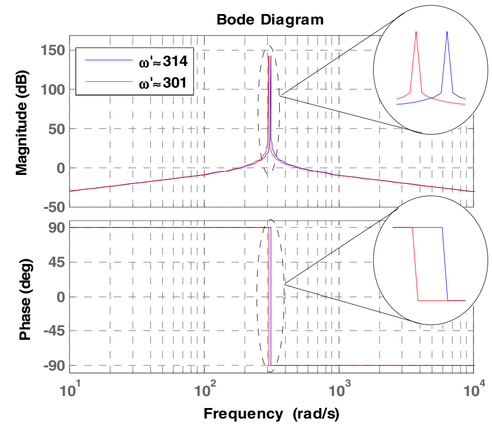

Fig. 3. Bode diagram of SOGI-FLL with different frequencies and constant "k" value

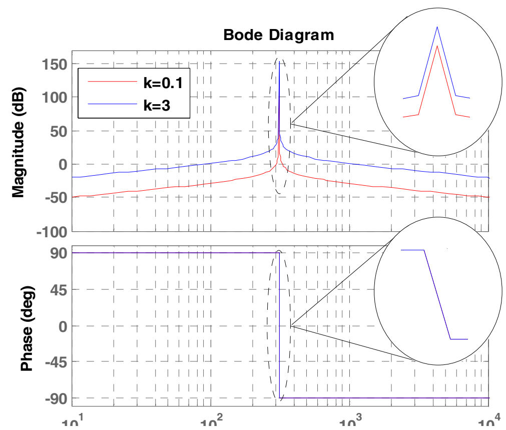

Fig. 4. Bode diagram of SOGI-FLL with different values of "k" and constant frequency

At first, the distorted load terminal voltage is sampled and decomposed into different sinusoidal signals in different frequency scope using FIR filter. Low-pass and band-pass filters are used to implement this aim. The FIR filter coefficients are different if the cutoff frequency in low-pass filters is set in different value, and the filtering results are different. It is assumed that the harmonic frequencies are greater than 50Hz. For fundamental frequency, a low-pass FIR filter with a cutoff frequency of 60Hz is used. Second, the resulted signal is reconstructed using IDWT. The selection of the FIR filter order and IDWT reconstruction level are done by considering tradeoff between speed and precise of the response. So, with increasing the FIR filter order and IDWT level, the speed of the response decreases and its precise increases, and vice versa. Therefore, in this paper the FIR filter order and IDWT reconstruction level are considered 3 and 4, respectively.

On other hand, as shown in Fig. 2, a controller based on fuzzy logic, called FLC, is used to adjust SOGI-FLL gain. By using FLC in SOGI-FLL structure, the frequency and reference phase tracking in a distorted power system with oscillation frequency is yielded fast and accurately. Steps of FLC implementation are as following:

- Defining ε_f and $\Delta\varepsilon_f$ variables as inputs of fuzzy controller block, ε_f and $\Delta\varepsilon_f$ are frequency error and differential rate of frequency error, respectively.
- Defining fuzzy levels to exchange the crisp and numerical values to linguistic variables, PB (positive big), P (positive), Z (zero), N (negative), NB (negative big) are input fuzzy levels and S (small), M (medium) and L (large) are output fuzzy levels.
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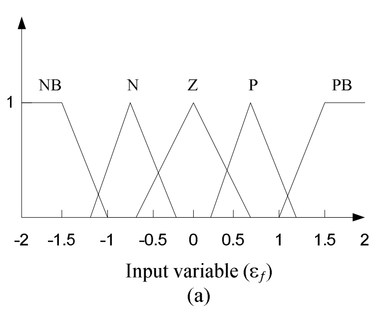
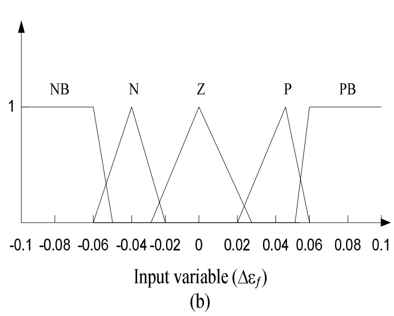
- Defining membership functions (MF) and draw related plots; membership function is a curve mapping every points of input environment to a membership value, called degree of membership (DOM). These values are between 0 and 1. MFs are plotted in Fig. 5. DOM of inputs can be illustrated as bellow.

$$\Psi_{N,Z,P}(\chi) = 1 - \frac{|\chi - m|}{0.5w} \tag{12}$$

$$\Psi_{P,B}(\chi) = -\Psi_{N,B}(\chi) = \begin{cases} 0 & \chi < 1 \\ \left(\frac{1}{m-1}\right)(\chi - 1) & 1 < \chi < m \quad , |m| > 1 \\ 1 & \chi > m \end{cases} \tag{13}$$

where, w is the width of function amplitude, x is input signal variable, and m is the coordinate of the point where DOM is equal to one.





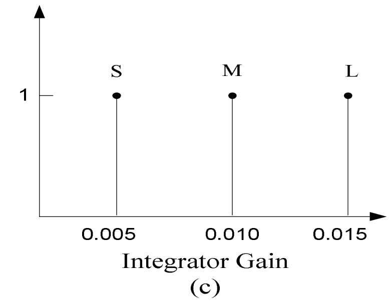


Fig. 5. Membership functions, (a) frequency error (ε_f), (b) differential rate of frequency error ($\Delta\varepsilon_f$) and (c) output signal of FLC or integrator gain

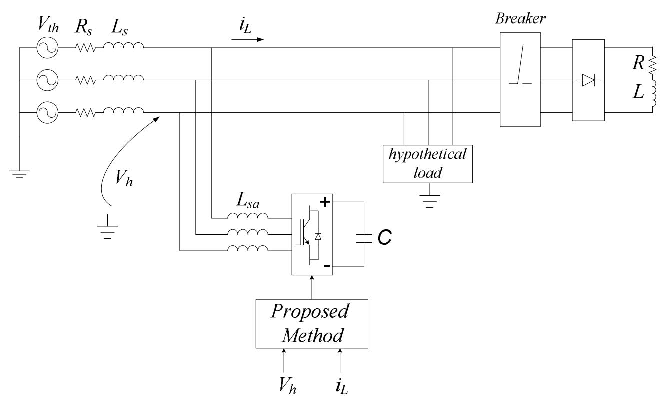


Fig. 6. Studied power system

III. Simulation Results

Fig. 6 demonstrates studied power system. In this voltage distorted power system two different scenarios are reported. Load increases and frequency drops are applied one by one at t=0.1sec. Figs. 7 and 8 show the current waveforms of unbalanced load and compensated source side by proposed method, respectively.

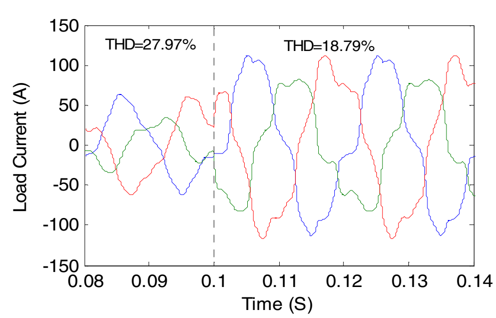


Fig. 7. Load current when load increases at t=0.1sec

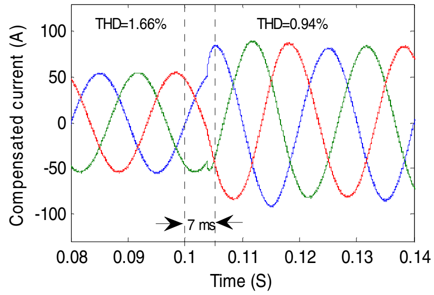


Fig. 8. Compensated current when load increases at t=0.1sec

According to Fig . 8, compensated current has high precise (THD≈1%) and is below the standard limit recommended by IEEE standard 519 and has low delay (less than half cycle). The idea of fast response refers to the fact that, whenever load current changes, forgetting factor quickly returns to the less than one and as a result covariance matrix will be reset and will have instant increase. This increasing will speed up estimation procedure. Figs. 9(a) and (b) portrait covariance matrix and forgetting factor changes for each of main component estimator of three phase load current under load changing, respectively.

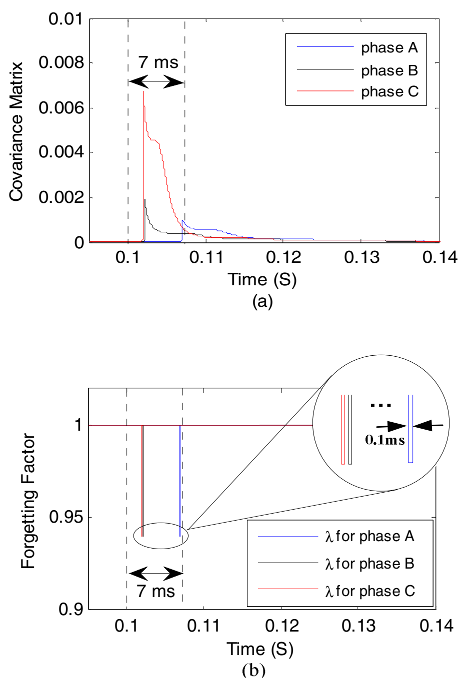


Fig. 9. Parameters variation of designed fundamental component estimator based on VFF-RLS under load changing (a) the main element of covariance matrixes $[P]_{1\times1}$ and (b) forgetting factors

The prominent feature of proposed SOGI-FLL based on FLC controller and FIR filter with respect to other techniques, is its fast and accurate tracking ability in polluted and variable frequency environment. In order to approve this feature, as the second scenario, the power system frequency suddenly changes from 50 Hz to 48 Hz in the presence of constant load. This frequency decrement of 4% is twice as high as the maximum admissible variation based on the IEEE standard 446 in power system. Figs. 10 and 11 depicted the current waveforms of unbalanced load and compensated source side by proposed method, respectively. Table I shows summery of proposed compensation performance in various phenomena.

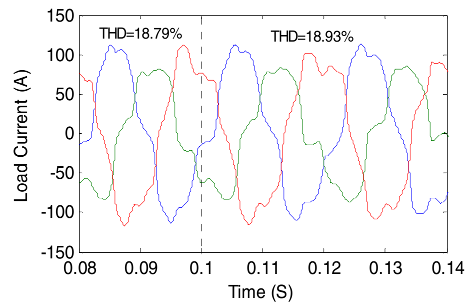


Fig. 10. Load current when frequency changes at t=0.1sec

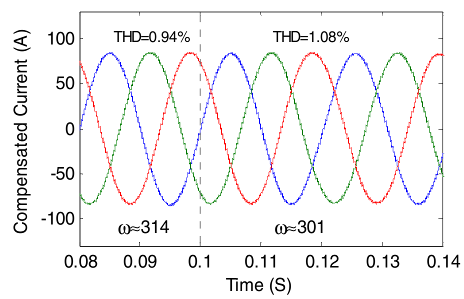
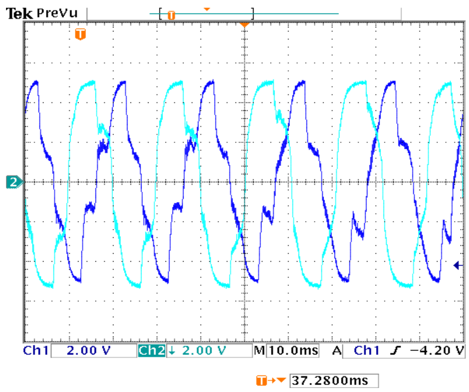


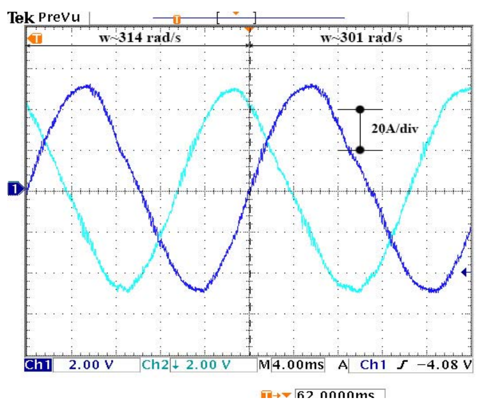
Fig. 11. Compensated current when frequency changes at t=0.1sec

IV. Exprimental Results

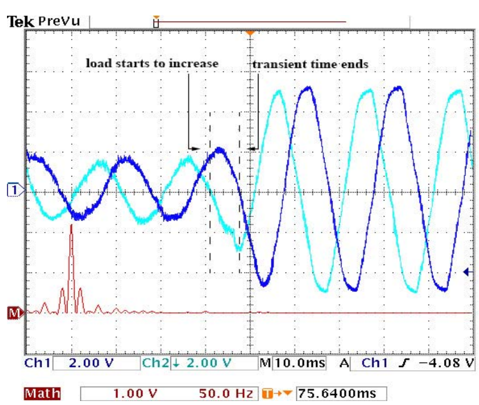
In order to validate simulation results, some of the simulated scenarios have been implemented using Texas TMS320F2812 digital signal controller (DSC) as a control system of proposed APF. Generated control signals have been applied to the three-phase IGBT inverter that has been implemented by three Semikron SKM 75GB128D half bridge IGBT modules. In order to measure and generate suitable feedback system, instrumentation system contains three LEM-LV25-P and LA25-P voltage and current transducers. The measured voltages and current signals have been sent to DSC control system to generate and control suitable signals for IGBT switches. In this three phase system, two phase's waveforms (phases "A" and "B") are presented. Figs. 12(a), (b), (c) and (d) show the waveforms of unbalance load and compensated source side currents in before mentioned scenarios, respectively. The scale of the all figures is 100mV/A.



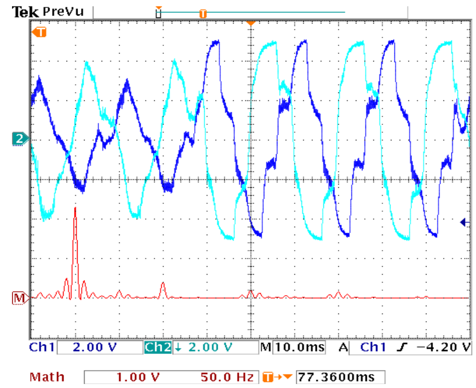
(a)



(b)



(c)



(d)

Fig. 12. Experimental results of proposed control method (a)load current in the presence of frequency oscillation,(b) source current in the condition of (a), (c) source current in the condition of load increasing, (d) load current in the condition of (c)

TABLE I. COMPENSATION PERFORMANCE OF SUGESTED METHOD IN VARIOUS PHENOMENA

Occurred Phenomena	The amount of parameter changes	Compensated Current		
		THD (%)		Delay (ms)
		Before change	After change	
Load Change	Increasing	1.66	0.94	7
Frequency Change	-2 Hz	0.94	1.08	22
Phase Jump	-50 Degree	0.94	0.96	35
Sag	-0.1 pu	0.94	1.19	20
Swell	0.1 pu	0.94	1.23	20

V. CONCLUSION

In this paper a novel control structure is proposed for APF, based on VFF-RLS and SOGI-FLL employing WT and FLC in distorted voltage condition. This structure would be well performed under load voltage increase/decrease, sag/swell and phase jump and oscillation frequency. At first, harmonic component of load current and it's positive sequence are estimated with VFF-RLS. Independency on order and amplitude of harmonics, fast dynamic and high accuracy is the bold features of designed estimators. Secondly in order to compensate an infected power network with oscillation frequency, SOGI-FLL based on WT and FLC has been proposed to track the reference phase of network in the best manner. Efficiency of the discussed method in a three-phase power system has been validated using both simulations in MATLAB and experimental results.

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