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Active Shunt Filter for Harmonic Mitigation in Wind Turbines Generators

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Abstract-This paper proposes a new unified active filter so as to perfectly alleviate instantaneous unwanted oscillation of powers as they may lead frequency variations in weak systems due to the torque oscillations. First it presents negative impacts of capacitive loads on the shunt active power filter performance in compensation of the instantaneous oscillation of the real power. Second, an advanced universal power quality conditioning system (A-UPQS) is introduced for three-phase four-wire systems under non-ideal waveforms. Considering the suggested compensation algorithm, the advanced UPQS is able to extremely suppress instantaneous oscillating powers caused by the distorted-unbalanced load-terminal voltages. Moreover, an independent single-phase converter is suggested at the load-end in order to regulate the DC-link voltage. Therefore, the instantaneous oscillating powers perfectly suppress and thus, source-end three-phase currents would be purely sinusoidal. The suggested A-UPQS is used to stabilize micro grid frequency. The effectiveness and flexibility of the proposed Advanced UPQS is confirmed by Matlab/ Simulink simulations.

Index Terms—A-UPQS, DC bus, Load-Terminal Voltage, Unified Power Quality Conditioning system.

I. INTRODUCTION

Rapid growth of power electronics loads leads to lots of power quality problems such as harmonics, unbalancing and excessive source-end neutral current in three-phase supply networks. These power quality problems cause many adverse effects like errors in measuring instruments, increasing of harmonics, false operation of circuit breakers and relays, reduction of transmission system efficiency, malfunctioning of electronic equipment and overheating of transformers [1]. A compensation algorithm is a commanding sub-system for shunt filters, extracting the reference signals from load-terminal currents and voltages at the point of common coupling. The applied control algorithm has to evaluate the current components properly to afford elimination of undesirable source-end current components with respect to higher harmonics, reactive power and negative sequence components of the load current. The control algorithm is derived based on electrical power theories, defined in the time domain. One of most important theories for planning the compensation algorithm is the OS (optimal solution) proposed in [2],[3], The OS is simple to implement, but it is proper only for three-wire balanced systems. Even when a three-wire system contains negative voltage component, compensation with the OS leads to have distorted source-end current. To provide credible results for such systems, generalized theory of instantaneous power (GTIP) definition was proposed [4]. In [5],[6] the GTIP has been derived, and the OS is clarified as the root of the generalized theory of instantaneous power definition. Although the compensation algorithm based on GTIP has an acceptable performance in three-phase four-wire balanced systems, it leads to have distorted source-end zero sequence current under non-ideal wave forms [7]. Other prominent proposed power theory are the FBD (Fryze_Buchholz_Depenbrock) by Depenbrock [8], CPC (Current’s Physical Component) which in the frequency domain, interprets and describes power phenomena in three-phase three-wire systems by Czarnecky [9], the CPT (Conservative Power Theory) by Tenti [10] and the p-q-r theory in[11]-[13], which is defined in the α-β-0 reference frame. A comparison of the p-q with the p-q-r theories is afforded in [13]. The control algorithms based on these power theories result in unsatisfactory outcomes when the load-terminal voltages are unbalanced and distorted [6], [7]. In our previous works, advanced GTIP (A-GTIP) theory was proposed as a solution to provide accurately reference signals for active power filters. It has been shown that the A-GTIP theory is proper for any three-phase four-wire circuit conditions [5], [7].

Increasing of power quality problems such as voltage harmonics and source-end current distortions in three-phase supply networks cause active power filters have found vital application for mitigating of terminal-load voltage and source-end current harmonics as well as eliminating of instantaneous active power oscillations and compensating of reactive power. Relying upon the requirements an activating algorithm and a formation which have to be chosen properly provides this wide range of objectives either individually or in combination. In [14], shunt active power filter (SAPF) is introduced to eliminate power oscillations. It will be presented that shunt active filters even under the compensation algorithm based on A-GTIP, produce unacceptable performance in the presence of capacitive loads (with very low ZL). Some modern solutions in form of unified power quality controller (UPQC) and universal power quality conditioning systems (UPQS) were proposed for fully power compensating in three-wire networks [15], [16]. The compensation algorithms of the shunt part of these unified active filters are resulting in unsatisfactory outcomes when the load-terminal voltages are unbalanced and distorted [7], [17], [18]. This paper intends to perform vital corrections on the shunt filter activating algorithm for the aforementioned unified power compensators for a satisfactory power compensation and harmonics alleviation especially in three-phase four-wire systems. The paper is proposed an advanced universal power quality conditioning system (A-UPQS) which leads to purely sinusoidal source-end currents under both distorted-unbalanced load-terminal

voltages and capacitive load conditions. Moreover, the isolated DC-link voltage regulating converter is connected to just one-phase at the load-terminal side, therefore, unlike a previous proposition of a three-phase converter at the source-end, the new suggestion will be able to regulate the DC-link without any distortion. The current distortions and harmonics, generated by independent single-phase converter, would be nullified by the shunt filter of the proposed A-UPQS. At the end, the proposed unified compensator is applied to micro-grids, which generally are feeble systems. In a micro-grid, frequency variation may appear due to the oscillation in the load or oscillation in the renewable energy sources like wind power [19]. Micro-grids mainly have torsional torque vibration that could be damped to avoid frequency variation by active filter [14], [20].
The paper is organized as follows. In section II, the structure of general unified compensators is presented. By introducing a compensation algorithm based on advanced generalized theory of instantaneous power (A-GTIP), advanced UPQS is proposed in three-phase four-wire systems in section III. Finally, in section IV the stability of micro grid frequency due to the pliability and effectiveness of the proposed A-UPQS to compensate power oscillations, is verified by matlab/sinulink simulations.

II.THE STRUCTURE OF GENERAL UNIFIED POWER QUALITY CONTROLLER

Basic structure of a general unified power quality controller (UPQC) as shown in fig.1 consists of the combination of shunt-active and series-active filters.

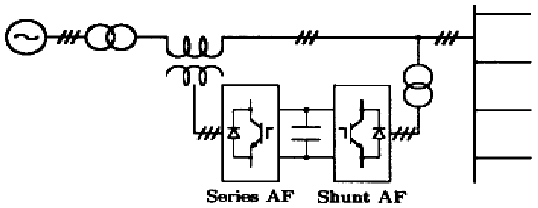


Figure.1. General unified power quality conditioner (UPQC)

• **Shunt filter:** Shunt active power filter (SAPF) is used to eliminate load-terminal current harmonics and leads to purely sinusoidal source-end currents. The control block diagram of general shunt active power filters is shown in fig.2. A hysteresis current comparator is used to track the current command to generate a proper PWM waveform to trigger the power switches of converter.

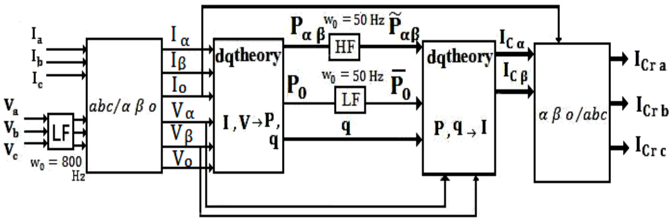


Figure.2. General Shunt active filter controller block diagram

The generalized theory of instantaneous power definition (GTIP) is usually used for reference signal determination in control schemes for shunt active filters.

III. SHUNT ACTIVE FILTER MALFUNCTIONING

a. Let us suppose that $\mathbf{v}(t)$ involves all sequences ($\mathbf{v}(t) = \mathbf{v}^{+}(t) + \mathbf{v}^{-}(t) + \mathbf{v}^{0}(t)$, where $\mathbf{v}^{+}(t)$, $\mathbf{v}^{-}(t)$ and $\mathbf{v}^{0}(t)$ positive, negative and zero sequences of $\mathbf{v}(t)$), respectively. Therefore, the source-end currents, using the OS [2, 3], can be rewritten as:

$$\begin{cases} \begin{cases} i_s(t) = i_s^{+}(t) + i_s^{-}(t) + i_s^{0}(t) \\ i_s^{+}(t) = \lambda v^{+}(t) \\ i_s^{-}(t) = \lambda v^{-}(t) \\ i_s^{0}(t) = \lambda v^{0}(t) \\ \lambda = \dfrac{\bar{p}(t)}{v(t).v(t)} \end{cases} \\ \begin{cases} i_s(t) = \dfrac{\bar{p}(t)}{V(t).V(t)} V(t) \\ i_c(t) = i(t) - \dfrac{\bar{p}(t)}{V(t).V(t)} V(t) \end{cases} \end{cases} \tag{1}$$

Due to the fact that the non-sinusoidal V(t) in the term V(t).V(t) in equation (1) acts as the source of distortion, the SAPF compensation algorithm will inject a distorted current. Therefore, the compensation algorithm derived from the GTIP under the both asymmetric and distorted three-phase load-terminal voltages provides unacceptable outcomes. The A-GTIP theory is proposed further solution to overcome these defects:

- One suggestion to overcome voltage asymmetry is to replace $\mathbf{v}(t)$ by $\mathbf{v}^{+}(t)$ in (1). Hence, the new source-end currents and the shunt active injected currents obtained as follows:

$$\begin{cases} i_s(t) = \dfrac{\bar{p}(t)}{V^{+}(t).V^{+}(t)} v^{+}(t) \\ i_c(t) = i(t) - \dfrac{\bar{p}(t)}{V^{+}(t).V^{+}(t)} v^{+}(t) \end{cases} \tag{2}$$

- As long as $v^{+}(t)$ doesn't include any harmonic components, the source-end currents remain purely sinusoidal. Otherwise, the non-sinusoidal $v^{+}(t)$ in the term $V^{+}(t).V^{+}(t)$ acts as the source of distortion; therefore, the SAPF compensation algorithm will inject a distorted current. The new injected current of the shunt active filter would lead to a sinusoidal source-end currents in four-wire systems by defining $v_1^{+}(t)$ as the fundamental component of $v^{+}(t)$ as follow:

$$\begin{cases} i_s(t) = \dfrac{\bar{p}(t)}{v_1^{+}(t).v_1^{+}(t)} v_1^{+}(t) \\ i_c(t) = i(t) - \dfrac{\bar{p}(t)}{v_1^{+}(t).v_1^{+}(t)} v_1^{+}(t) \end{cases} \tag{3}$$

The proposed shunt active filter controller block diagram is shown in fig.3.

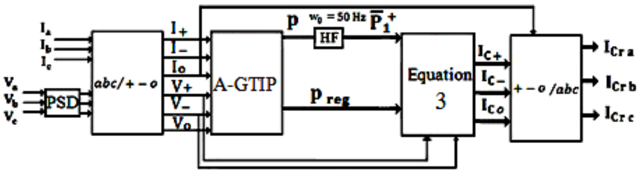


Figure.3. Proposed compensation algorithm (based on A-GTIP theory) block diagram

Unlike the previous proposition of shunt filters, as shown in our previous works, compensation algorithm based on the advanced GTIP theory for controlling the active compensator, result in eliminating of all the distorted-unbalanced load-terminal voltages.

b. Shunt active filter produces controlled current in order to compensate harmonic and unbalanced currents drawn by the non-linear loads. The principles of shunt current injection can be explained base on fig.4.

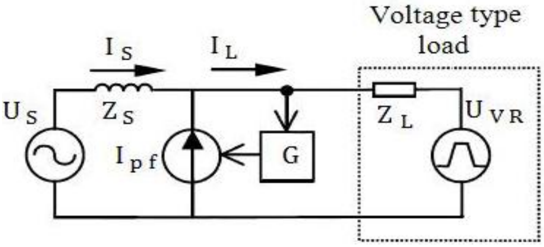


Figure.4. Shunt active filter compensation of voltage type loads

If magnitude of injected current of shunt filter (Ipf) be equal to the load harmonics in reverse phase, the shunt active filter generates satisfactory outcomes and leads to purely sinusoidal source-end currents.

$$\begin{cases}\begin{cases}I_{pf}=G(jw).I_L \quad ,G(jw)=\begin{cases}0 & w=w1\\ 1 & w=wh\end{cases}\\ KCL: I_S=\big(1-G(jw)\big)I_L\\ KVL: U_S=Z_SI_S+Z_L\left(I_S+G(jw)I_L\right)+U_{VR}\end{cases}\\ \qquad\begin{cases}I_L=\dfrac{1}{1-G(jw)}*\dfrac{U_S-U_{VR}}{Z_S+\dfrac{Z_L}{1-G(jw)}}\\ I_S=\dfrac{U_S-U_{VR}}{Z_S+\dfrac{Z_L}{1-G(jw)}}\end{cases}\end{cases} \qquad (4)$$

If for $w=w_h$, $\left.\frac{Z_L}{1-G}\right|_{w=w_h} \gg Z_s|_{w=w_h}$, then I_L (load current) and I_S (source-end current) are obtained as follows:

$$\begin{cases}I_L(w=w_h)=\frac{1}{0}*\frac{U_S-U_{VR}}{Z_S+\frac{Z_L}{0}}=\frac{U_S-U_{VR}}{Z_L}\\ I_S(w=w_h)=\frac{U_S-U_{VR}}{Z_S+\frac{Z_L}{0}}\approx 0\end{cases} \qquad (5)$$

Due to the fact that capacitive loaded diode rectifier leads to a very low Z_L, the upper equations even in the presence of A-GTIP compensation algorithm would not be fulfilled, and therefore, the shunt active filters cannot produce satisfactory outcomes. One solution is to utilize active series filters (SF).

• **Series Filter:** The series active power filters are used to compensate the source voltage deficiencies and forces capacitive load type harmonics to flow into the shunt filter. The SF inserts high impedance on harmonic frequencies in order to compensate harmonic currents drawn in the case of capacitive loaded diode rectifiers as shown in fig.5.

$$\begin{cases}U_{SF}=K.G(jw).I_S \quad , \qquad G(jw)=\begin{cases}0 & w=w1\\ 1 & w=wh\end{cases}\\ \qquad\begin{cases}KVL: U_S=Z_SI_S+Z_LI_S+U_{Sf}+U_{VR}\\ I_S=\dfrac{U_S-U_{VR}}{Z_S+K.G(jw)+Z_L}\end{cases}\end{cases} \qquad (6)$$

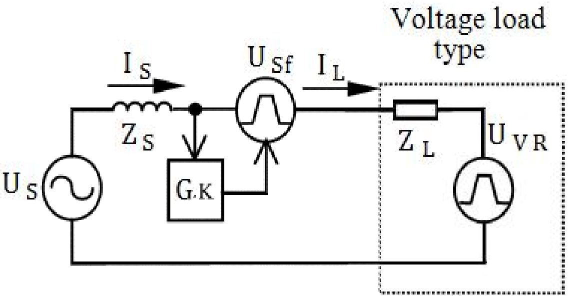


Figure.5. Series active filter supplying current and voltage type loads.

In equation (6) k is the impedance gain in harmonic frequencies. If $K \gg |Z_S+Z_L|_{w=w_h}$ is fulfilled then the further result would be obtained:

$$\begin{cases}I_S(w=w_h)=\frac{U_S-U_{VR}}{Z_S+K.G(jw_h)+Z_L}\approx 0\\ U_{sf}\approx Z_L.I_L(w=w_h)+U_S(w=w_h)\end{cases} \qquad (7)$$

Figure 6 introduces a typical series active filter suitable for simulation and designing purposes.

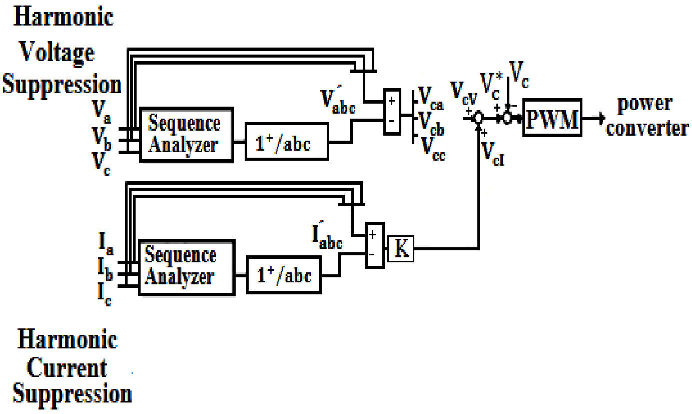


Figure.6. Series active filter controller single-phase block diagram

In the harmonic voltage suppression loop, the fundamental component of line voltage is extracted from the measured source voltage to mitigate voltage deficiencies. The main current harmonics are obtained by subtracting the positive fundamental current component from the measured source-end currents. The output voltage of the converter for harmonic current suppression is obtained from the multiplication of the calculated mains harmonic current and the equivalent harmonic resistor (K).

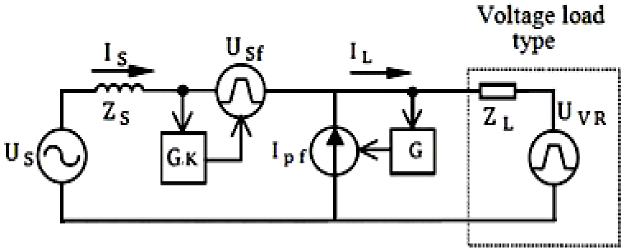


Figure.7. Combination of series and shunt active filter controller single-phase block diagram

As shown in fig.7, the combination of unified shunt and series active filter produces satisfactory outcomes and therefore, a full harmonic cancellation would lead to sinusoidal source-end currents (8).

$$\begin{cases}\begin{cases}\begin{cases} I_{pf} = G(jw).I_L \\ U_{SF} = K.G(jw).I_S \end{cases} , G(jw) = \begin{cases} 0 & w = w1 \\ 1 & w = wh \end{cases} \\ \text{KCL}: I_S = \left(1 - G(jw)\right) I_L \\ \text{KVL}: U_S = Z_S I_S + Z_L (I_S + G(jw) I_L) + U_{Sf} + U_{VR} \end{cases} \\ \begin{cases} I_L = \dfrac{1}{1 - G(jw)} * \dfrac{U_S - U_{VR}}{Z_S + K.G(jw) + \dfrac{Z_L}{1 - G(jw)}} \\ I_S = \dfrac{U_S - U_{VR}}{Z_S + K.G(jw) + \dfrac{Z_L}{1 - G(jw)}} \approx 0 \\ U_{sf} \approx Z_L.I_L(w = w_h) + U_S(w = w_h) \end{cases} \end{cases} \quad (8)$$

Due to the fact that UPQC has a limited power factor compensation capability [16], an independent three-phase converter at the source side is used to regulate DC-link voltage by an isolated control circuit as shown in Fig. 8.

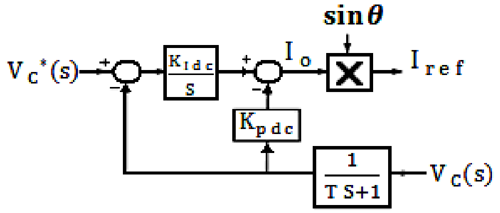


Figure.8. Control of active rectifier

The independent converter leads to activating algorithm simplicity and decreasing the element's power density. The independent DC-link three-phase converter of UPQC at the source side, although, removed the limitation of power factor compensation capability, it leads to source-end current distortions and harmonics. The universal power quality conditioning system (UPQS) is shown in fig.9.

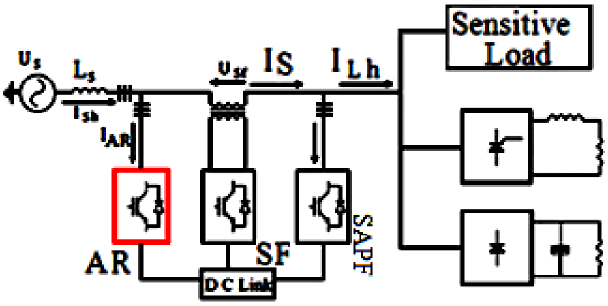


Figure.9. Universal power quality conditioning system (UPQS)

Fig.9. shows that active rectifier and SAPF have a three-phase three-wire topology, while the series filter has a three-phase four-wire topology. These aforementioned forms of compensators are practically true for three-phase systems as long as load-terminal voltages remain balanced and sinusoidal. Nevertheless, when the power system is unbalanced and distorted in a three-phase four-wire system, due to the malfunctioning of the compensation algorithm that derived from d-q or α-β-0 theories, the unified compensators introduce unsatisfactory cancelling of the source zero sequence current and harmonics suppression.

IV. ADVANCED UNIVERSAL POWER QUALITY CONDITIONING SYSTEM (A-UPQS)

The proposed A-UPQS includes the combination of the shunt active filter, series active filter, and an independent single-phase rectifier. It is shown that, although, shunt active filter, activated by the compensation algorithm based on A-GTIP theory equ(3), leads to satisfactory performance under distorted and unbalanced load-terminal voltages in three-phase four-wire systems, it does not still lead to fully compensating especially in the capacitive load conditions. Therefore, the series active filter is suggested as a complementary for shunt filter. Moreover, by connecting the independent single-phase converter at the load side, unlike the previous proposition of a three-phase converter at the source side, it would be able to regulate the DC-link without any current distortions and harmonics, because the shunt filter of the proposed A-UPQS would nullify these negative effects, generated by independent single-phase converter. So, the proposed A-UPQS leads to nullifying the current distortions and harmonics in any conditions. Fig.10. shows the proposed A-UPQS.

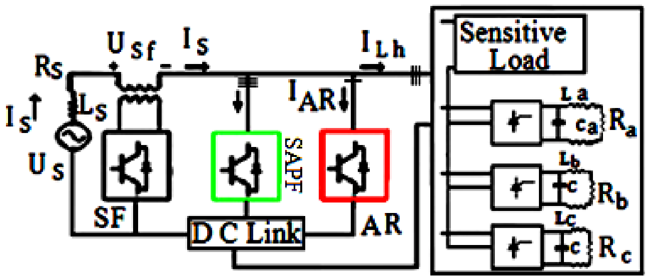


Figure.10. A-UPQS block diagram

V. FREQUENCY CONTROL IN A MICRO-GRID

In this section, some simulations will be designed to verify the pliability of A-UPQS considering a micro-grid application. The present simulation involves an 11 MW wind farm consisting of five wind turbines, a synchronous generator and the A-UPQS active filter (see fig.11, 12.) the detailed characteristics of which can be observed in tables 1 and 2. It is assumed that the reactive power, produced by wind turbine, equals zero.

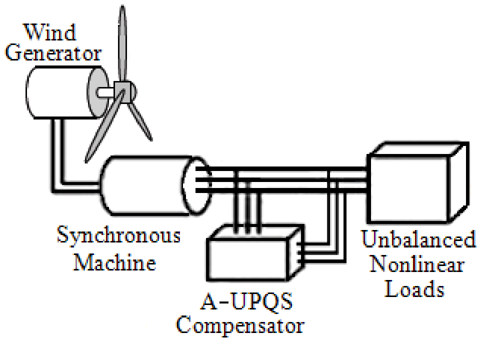


Figure.11. Simulated micro-grid involved nonlinear unbalanced load and Power Compensator

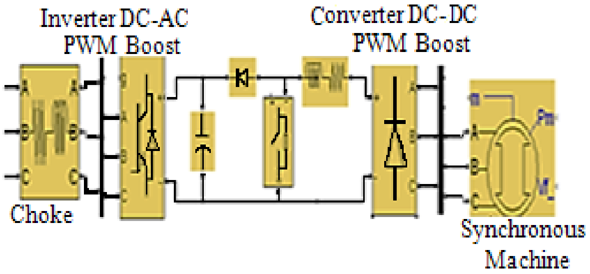


Figure.12.Synchronous generator block diagram in wind farm

In this model a synchronous generator is connected to the distributed system through a rectifier, both boost PWM DC-DC converter and PWM DC-AC inverter use IGBT switches. The variable velocity of the wind turbine is normalized on the base of 11 m/s for duration of 0.6 second in per unit, as shown in fig.13. Also, the non-linear load of fig.14 consists of three single-phase rectifiers that feed the following circuit elements:

$$\begin{cases} R_a = 10/3\,\Omega, & L_a = 60e^{-3}H, C_a = 0.3mF \\ R_b = 10\,\Omega, & L_b = 60e^{-3}H, C_b = 0.2mF \\ R_c = \dfrac{10}{3}\Omega, & L_c = 60e^{-3}H, C_c = 0.3mF \end{cases}$$

A passive LCL-filter is used to attenuate the unwanted frequency components resulting from the switching modulation of shunt part of the A-UPQS. Parameters of the converter and the LCL-filter are tabulated in Table 3 [21].

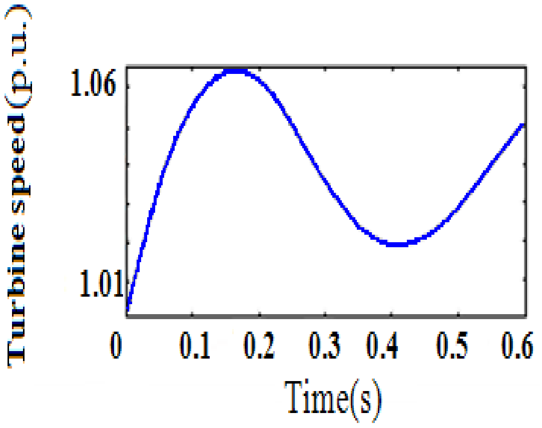


Figure.13.velocity of Wind Turbines

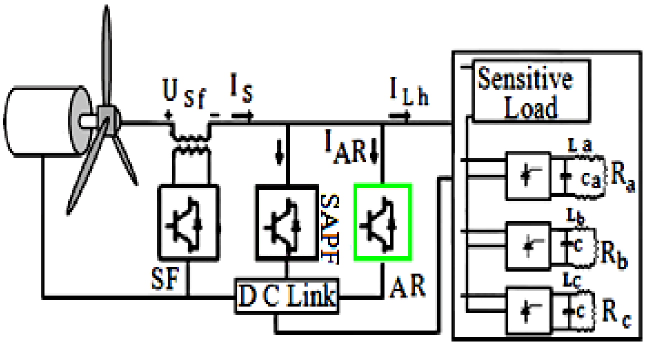


Figure.14. A typical interconnection of the source, the load and the A-UPQS compensator

In this simulation a hysteresis current control modulation technique is employed that drives the switches with variable frequencies [22]. Figures 15 show the source-end currents before and after the compensation by proposed A-UPQS in three-phase four-wire system respectively. This simulation shows that current distortions have been extremely decreased. Figures 16, 17 respectively show the real power (p) and imaginary power (q) before and after proposed A-UPQS is connected to Micro-Grid respectively. It can be seen p̃ and q are perfectly compensated. So, with respect to the frequency controlling, torsional torque oscillations in micro-grids will be alleviated, and the maximum electrical micro-grid efficiency will be assured.

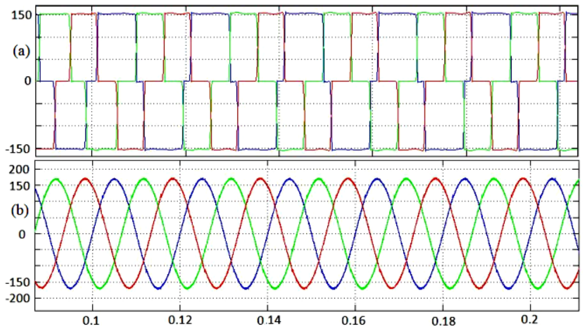
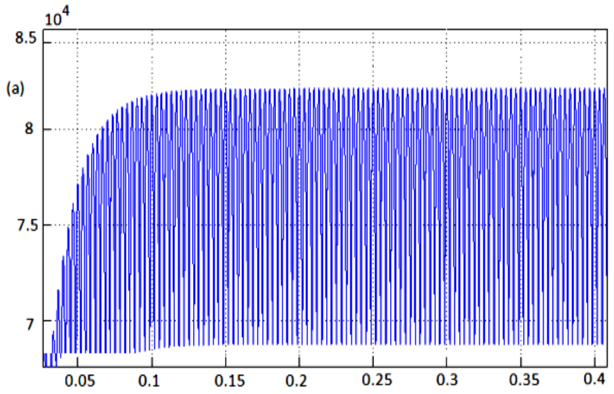
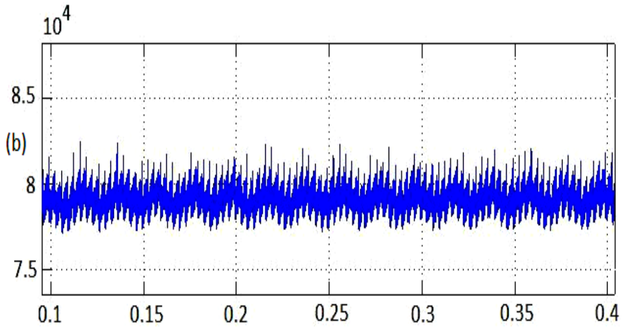


Figure.15. The source-end currents in three-phase four-wire system (a) before compensation (A) (THD 23.63%), (b) after compensation (THD 0.97%).

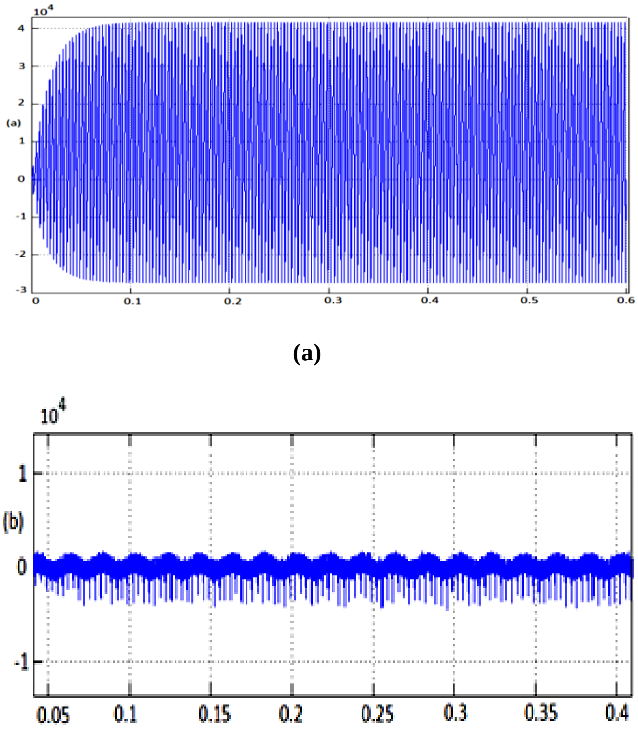


(a)



(b)

Figure.16. Micro grid real power (a) before compensation, (b) after compensation



(a)

(b)

Figure.17. Micro grid imaginary power (a) before compensation, (b) after Compensation

VI. CONCLUSION

An advanced unified power conditioning system that is able to fully cancel the real and imaginary oscillating powers under any distorted unbalance conditions in micro grids was proposed. The paper showed that not only both p-q and p-q-r theories, generally used in the compensation algorithm of shunt part of the unified compensators, are unable to fully compensate the unbalance components as well as distortions, but also the compensation algorithm based on the new A-GTIP theory for the shunt active filters would not lead to fully compensate especially for the capacitive loads. The proposed A-UPQS used complementary series active filter for eliminating the shunt filter malfunctioning. Further, a single-phase converter, connected to the load-side, regulates the DC bus of the A-UPQS. This enables the A-UPQS to suppress the disturbances of previously suggested three-phase converter at the source-end. The proposed A-UPQS was applied to a micro grid. The simulation results showed that the proposed A-UPQS would lead to eliminating unwanted instantaneous powers and alleviating the torsional torque oscillations and therefore, the efficiency and effectiveness of the micro grids would be assured.

APPENDIX

TABLE I: SYNCHRONOUS GENERATOR PARAMETERS

Parameter	Value
Available power	2 MW
voltage	575 V
poles	2
Power factor	0.9
Inertia	0.62 Sec.
Stator Impedance (p.u.)	0.006
Stator Reactance (p.u.)	1.485

TABLE II: WIND FARM PARAMETERS

Parameter	Value
Number	5
Shaft damping coefficient(p.u)	80.27
Inertia coefficient	4.32 Sec.

TABLE III: SWITCHING COMPENSATOR PARAMETERS

SAPF side LCL filter inductance L_1	4.1[mH]
Grid side LCL filter inductance L_2	0.5[mH]
LCL filter capacitor C_f	10 [μH]
LCL filter damping resistor R_f	20 [Ω]
SAPF Switching frequency	6:9[kHz]
SAPF DC-link capacitors (each one)	2 [mF]
SAPF DC-link voltage	700 [v]

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