ACTIVE FILTERING AND STABILITY ANALYSIS FOR HYBRID RENWEABLE NANOGRID

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Abstract: The nanogrid is a small scale power system that consists of renewable and non-renewable power resources that supply power to nearby loads. The performance of the nanogrid is not totally satisfactory as large over shoot may occur in the output voltage, and current disturbances may occur at load side. Also power electronics system can become unstable when the source interface converters are connected to load interface converters rather than separate loads.

However, there are some considerations to improve the nanogrid response and extend its functionality towards harmonics mitigation.

Key words: *Nanogrid, Passive Filter, Active Filtering, Moving average filter, Resonant filter, Interface converter, Hybrid, Small Signal, Damping, Disturbance Rejecting, DC Bus Signaling (DBS).*

In this paper, the passive filter is designed to damp out the over shoot of the output voltage and to suppress the current disturbances from the load side to improve the system stability. The system still has low-order harmonics in the load voltage at frequencies that are lower than the resonance frequency of the filter. To solve this problem, the interface controller is used as an active filter to inject harmonics, as well as to interface AC loads to the nanogrid, this can reduce the size of the output passive filter. Active filtering is used to inject the same amplitude of harmonic voltages with an opposite sign to cancel out the grid harmonics.

1. Introduction

As the market for small-scale renewable energy systems is rapidly increasing, the need for power electronic converters also increases. With the use of power electronic interface converters, renewable sources can be connected directly to a distribution network or combined with other local generators, and loads to form an independent power system.

A nanogrid is a stand alone system that uses renewable and non-renewable sources to supply power to local loads. A nanogrid is similar to the microgrid concept [1, 2], but smaller in size than a microgrid. It has a capacity in the order of 2-20 kW. However, there are some considerations to improve the system response and extend the functionality of the DBS towards AC loads and harmonics mitigation.

Fig.1 shows the nanogrid architecture to connect these systems together, and also to an isolated load. The performance of the nanogrid is not totally satisfactory as large over shoots may occur in the load voltage, and current disturbances may occur at load side which affect the stability of the system [3].

For AC loads, the inverter is necessary in the system to produce a sinusoidal wave to supply loads or is used as an active filter to cancel out the nanogrid harmonics. Using DBS as an active filter to inject harmonics cancelation, as well as to connect AC loads to the nanogrid, this can reduce the size of the output passive filter. In this paper, the operation of the nanogrid with DC loads was discussed.
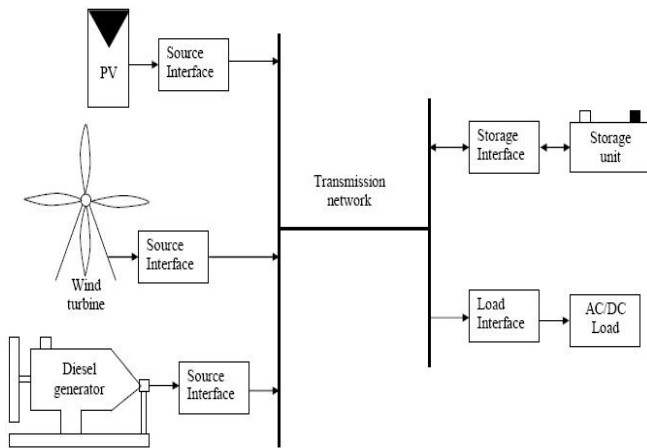
Fig.1 Nanogrid architecture.

A power electronics system can become unstable when the source interface converters are connected to load interface converters rather than separate loads. The performance of the DBS is not totally satisfactory as large over shoots may occur in the load voltage, and current disturbances may occur at load side which affects affect the stability of the system. A passive filter at load side is designed to damp out the over shoots of the load voltage and to suppress the current disturbances from the load side to improve the system stability [4].

Passive filters are used for harmonics mitigation, where they provide either a high impedance blocks to harmonics or a low impedance paths for harmonics. Thus, the current harmonics flow into the shunt filters instead of back to the supply. The passive filter consists of LC combination tuned for specific harmonics.

The drawbacks of passive filters are that they are strongly dependent on the system impedance, which depends on the distribution network configuration and the loads. Therefore, the system impedance, which changes continuously, strongly influences the filtering characteristics. In the worst case, an unwanted resonance can occur between the filter and the system. This may cause the passive filter to act as a ''sink'' for harmonics from other sources in the grid.

Therefore, the passive filter can be overloaded by a current higher than the rated value. Among the different new technical options available for harmonics mitigation, active power filters have proved to be an important and flexible alternative to passive filters. Active filters are gaining market share speedily as their cost becomes competitive with the passive variety. The load interface converter based active filter is by far the most common type used today, due to its well-known topology and straight forward installation procedure. The operation of active filters is based on injection of voltage harmonics out of phase with the load voltage harmonics, thus eliminating the harmonic content of the line voltage. When using active filters, it is possible to choose the voltage harmonics to be filtered and the degree of attenuation. The size of the converter can be limited by using selective filtering and removing only those voltage harmonics that exceed the standard level [5].

Also the system still has low-order harmonics in the load voltage at frequencies that are lower than the resonance frequency of the filter.

In this paper, to solve this problem, active filter is used to inject the same amplitude of harmonic voltages with an opposite sign to cancel out the nanogrid harmonics. The interface converter is used as an active filter to inject harmonics, as well as to interface AC loads to the nanogrid, this can reduce the size of the output passive filter.

2. Concept of Active Filtering

The idea of active filtering is relatively old, but its practical development was made possible with the new improvements in power electronics and microcomputer control strategies as well as with cost reduction in electronic components. Active filtering is performed based on the principle of voltage injection.

The controller of source interface converter can be modified to work as an active filter, where it injects the same amplitude of harmonic voltages with an opposite sign to cancel out the nanogrid harmonics [6].

A considerable attenuation of low-order harmonics in the load voltage can be clearly observed at frequencies that are lower than the resonance frequency of the output passive filter.

On the other hand, the input measured voltage to the control circuit contains some ripples that may affect the operation of the active filter.

Improving the filtering capability can be obtained by properly adjusting for each harmonic frequency, the reference voltage that the converter has to reproduce.

3. Design of Harmonics Mitigation Controller

The low-order harmonics in the load voltage can be clearly mitigated by modifying the load interface converter controller.

The controller of active filter consists of two main parts:-

1- Harmonics extraction: is the process in which, reference current is generated by using the distorted voltage and current waveforms. Many theories have

been developed such as p-q theory (instantaneous reactive power theory), d-q theory, PLL with fuzzy logic controller, neural network etc. Out of these theories, more than 60% research works use p-q theory and d-q theory due to their accuracy, robustness, and easy calculation.

In this paper, load interface converter controller has been modified to act as an active filter. It is also done by using d-q theory.

The main part of the controller is the Moving Average Filter (MAF) which is used for harmonics extraction. It separates the fundamental component of the measured voltage and current signals [6]. The moving average is the most common filter, mainly because it is the easiest digital filter to understand and use. The moving average filter is simple and effective. One disadvantage is the problem of lag associated with the moving average filter.

In equation form, MAF is written as:

$$y(i) = \frac{1}{N} \sum_{j=0}^{N-1} x[i+j] \qquad (1)$$

where: y is the output signal.

x is the input signal.

N is the number of samples in the sampling period.

Equation (1) leads to the transfer function of the MAF as a part of a discrete control algorithm as given below:

$$\frac{y(Z)}{x(Z)} = \frac{1}{N} \frac{Z^N - 1}{Z^N - Z^{N-1}} \qquad (2)$$
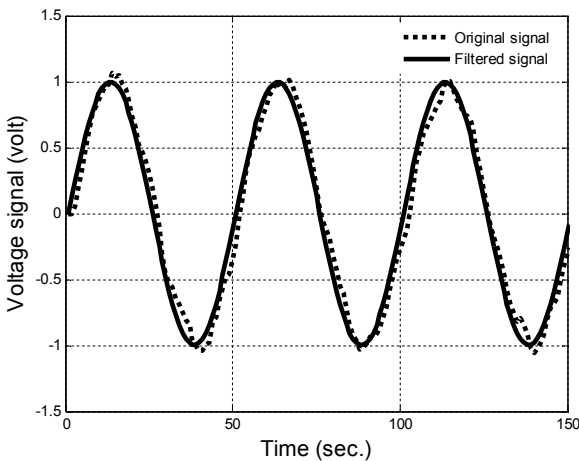

Fig.2 Response of MAF.

In d-q frame, if the measured signal is sinusoidal with only the fundamental frequency, this signal appears to the MAF as a dc component. In the presence of harmonics in the measured signal, it appears as a dc component but with superimposed oscillations, whose

frequency depends on the order of the present harmonics. The operation of the filter is investigated for a distorted signal as shown in Fig.2.

2- Current Modulator: Current modulator is mainly used to provide the gate pulse to the active power filter (Inverter). There are many techniques used for giving the gating signals, such as sinusoidal PWM, triangular PWM, hysteresis current controller etc.

In order to selectively cancel out the harmonic voltages, a Resonant Filter (RF) is used to estimate the harmonic voltage that should be injected by the active filter [7]. RF is a band pass filter used specifically to allow only a narrow range of frequencies through it.

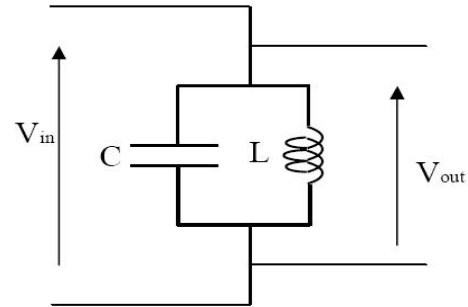RF circuit in its simplest form is shown in Fig.3:

Fig. 3 Basic circuit of RF.

Case 1:-

When the input frequency is very low, the reactance of the inductor will be very low, and the reactance of the capacitor will be very high. Current will therefore flow through the inductor rather than the capacitor. This means the output voltage will be negligible as the inductor is very small value.

Case 2: -

When the input frequency is very high, the inductor will be very high and the reactance of the capacitor will be very small. Current flows through the capacitor rather than the inductor as it has a lower reactance. Once again the output voltage at high frequencies will be negligible.

Case 3: -

At a mid range frequency, the reactance of both the inductor and capacitor has significant values and there will be some reactance in both parts of the circuit.

At resonant frequency the reactance of the inductor and capacitor will be equal. At this

frequency the maximum possible output voltage will be obtained. Thus, this filter produces low gain for all frequencies apart from the selected harmonic frequency with no phase shift, and injects the same amplitude of the selected harmonic voltages with an opposite sign.

The transfer function of RF is:

$$G(s) = \frac{K_f \, \omega_c \, (s + \omega_c)}{s^2 + 2\,s\,\omega_c + \omega_c^2 + \omega_n^2} \qquad (3)$$

where K_f is the filter gain, which is designed to obtain a unity gain at selected frequency.

ω_c is the band frequency (resonance frequency) in rad/sec to improve the transient performance of the filter.

$$\omega_c = \frac{1}{\sqrt{LC}} \qquad (4)$$

ω_n is the frequency of the selected harmonic in rad/sec.

To obtain a unity gain at selected frequency ω_n, the gain K_f should be equal to $2\omega_c$ under the assumption that $\omega_n \gg \omega_c$ [6].

In this analysis only the lowest-order harmonics, namely 5th, and 7th harmonics, have been considered. They may be denoted in general as harmonics of order n=6k±1 (with k=1).

For 5th harmonic order $\omega_n = 1570$ rad/sec., $\omega_c = 2\pi$ rad/sec. , $k_f = 4\pi$.

For 7th harmonic order $\omega_n = 2198$ rad/sec., $\omega_c = 2\pi$ rad/sec., $k_f = 4\pi$.

The discrete transfer function of the RF as a part of a discrete control algorithm is [4]:

$$G(z) = \frac{C_1 z^2 + C_2 z + C_3}{C_4 z^2 + C_5 z + C_6} \qquad (5)$$

where $C_1, C_2, C_3, C_4, C_5,$ and C_6 are constants for one selected harmonic frequency.
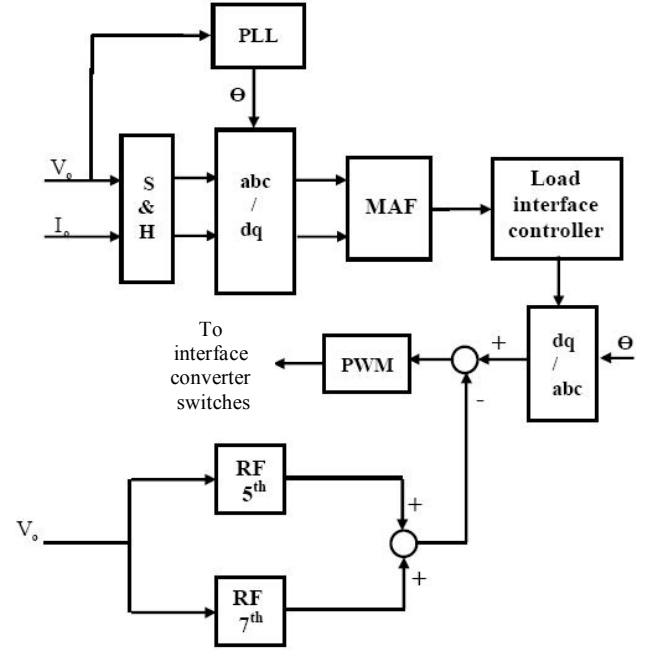

Fig.4 Block diagram of the modified controller for active filtering of load interface converter.

The block diagram of the control system is shown in Fig.4. A sampling time of T_s, sampling frequency f_s equals to the switching frequency is used [6]. The measured voltages and currents of the load (V_o, I_o) are sampled and held. The sampled quantities are provided to the dq transformation blocks to compute the direct axis "d" and the quadratic axis "q" quantities (two axis rotating reference frame) from three-phase quantities, the phase synchronous angle θ (more precisely [sin(θ), cos(θ)]) are obtained from the discrete phase locked loop (PLL). Thus measured quantities are only fundamental after separation of harmonics components using MAF.

Load interface controller controls converters' output voltage by providing the switching pulses to the interface converter. The RF injects the 5th and the 7th harmonics in an opposite direction to mitigate harmonics from the load voltage. The load voltage without an active filter is shown in Fig.5 (a). System parameters is given in table I.

The Fast Fourier Transform analysis (FFT) of the load voltage is shown in Fig.5 (b). Load voltage and its FFT when using an active filter is shown in Fig.6, which proves that the modified controller has filtered the 5th and the 7th harmonics from the load voltage and the total harmonic distortion has reduced from 13.9% without using active filter to 3.68% after using active filter.

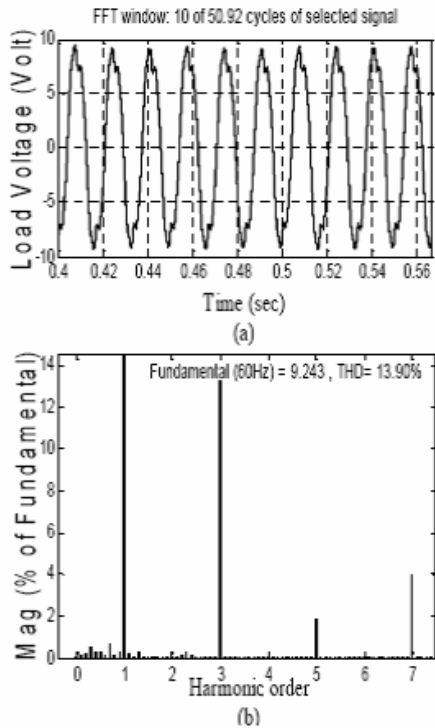FFT window: 10 of 50.92 cycles of selected signal

Fig. 5 Load interface converter output voltage without active filter: a) waveform of output voltage, b) spectrum of output voltage.
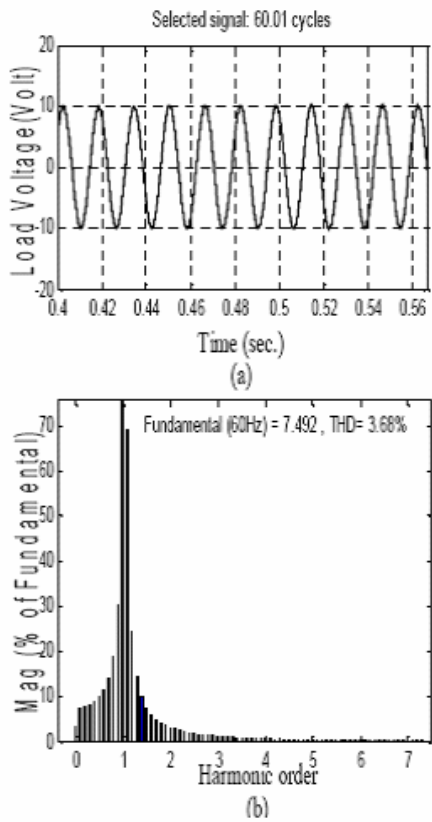

Fig.6 Load interface converter output voltage using active filter: a) waveform of output voltage, b) spectrum of output voltage.

Stability Analysis

When the source and load interface converters are designed in a standalone mode, there exists some instability when the modules are integrated into a system. Interaction can occur between the source and load interface converters [7,8], resulting in oscillations on the dc bus.

The system stability is determined by the ratio of the small signal output impedance to input impedance Z_o/Z_i [9], where Z_o is the output impedance of the source interface converter in conjunction with the effective transmission line impedance Z_{TL}, and Z_i is the cumulative input impedance of the load interface converters. The parameters of this definition are shown for a simple system in Fig.7.
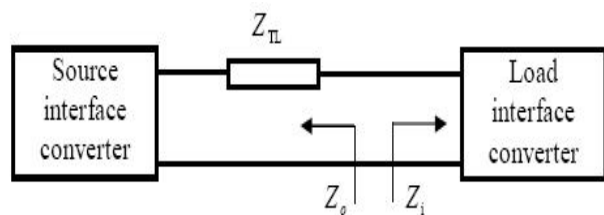

Fig.7 Small signal impedance in a power electronics system.

The Nyquist plot for a stable system is shown in Fig.8. The system becomes unstable if Z_o/Z_i encircles (-1,0) on the Nyquist plot.
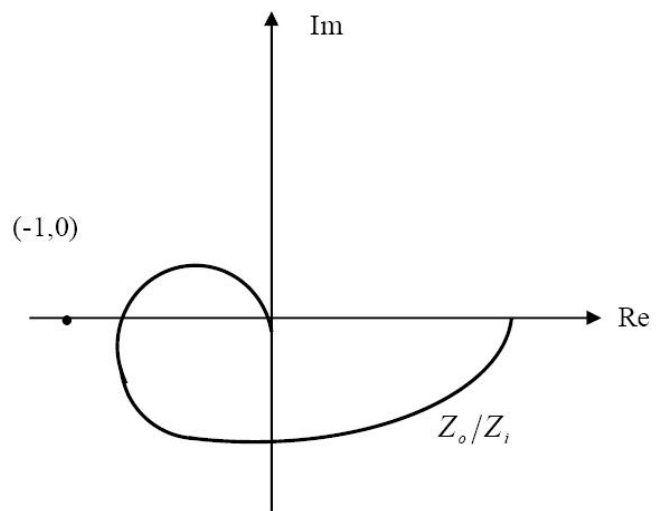

Fig.8 Nyquist plot for a stable power electronic system.

A recent contribution that proposes a less conservative design requirement for a distributed power electronics system is given in [10].

An alternative forbidden region is proposed to ensure stability of the system:

$$\mathrm{Re}\,(Z_o/Z_i) \rangle - \frac{1}{2} \qquad (6)$$

By designing the system such that Z_o/Z_i stays out of the forbidden region, stable operation of the system is ensured. The system exhibits a gain margin of 6 dB and a phase margin of 60°.

In a nanogrid, the structure of the system changes as additional sources come online to meet the fluctuating load demand or load shedding during supply shortage. Thus Z_o and Z_i change according to system structure changes. To ensure stability under all operating conditions, the operating condition that creates the largest output impedance must be accounted for.

To improve the system response, the control bandwidth of the load interface converters was reduced, damping was added to the system, and the bus capacitance was increased. These techniques have been shown to be successful in stabilizing a power electronic based dc system [11].

5. Passive Filter Design

To insure stable operation of interface converters at both load side and source side Fig.9, some specifications should be taken into account such as resonance in the output filters, and the control bandwidth. Increasing the control bandwidth is important for a fast operation of the interface converter. The maximum control bandwidth of the converter is limited physically by the cut off frequency of the output LC-filter.

However, very large over shoots may occur according to the LC output filter parameters since the converter must respond in almost step manner at transient state. The voltage over shoot with improperly selected LC-filter parameters goes through the load terminal and may bring malfunctions or trips on some sensitive loads.
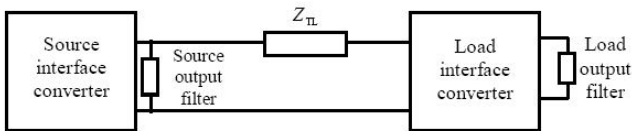

Fig.9 System structure when using LC-filter at output of interface converters.

Therefore it is necessary to consider both control system characteristics and converter size in designing output filters for interface converters.

The cut off frequency of the LC output filter determines the control bandwidth of interface converter systems and the attenuation against the switching ripple from the converter.
However, there are infinite combinations of filter inductance and filter capacitance for a given filter cut off frequency.

The load interface converter, instantaneously, must generate three controlled voltages simultaneously: the output voltage (U_{comp}), oscillation damping voltage (U_{damp}), and the disturbance rejecting voltage (U_{dist}). Fig.10 shows the equivalent circuit of the passive LC-filter.

To design the passive filter parameters (L_f, R_f, C_f), the following considerations should be taken into account :-

Compensation voltage: the output voltage (U_{comp}) regulates the output-injected voltage (U_{out}) of the inverter by pre-compensating the time delay of the LC-filter as [12]:

$$\frac{U_{out}}{U_{comp}} = \frac{1}{\left(1+s/\omega_f\right)^2} \qquad (7)$$

$$U_{compt} = \left(1+s/\omega_f\right)^2 . U_{out} \qquad (8)$$

where $\omega_f = \sqrt{1/L_f\,C_f}$ is the cutoff frequency of the filter.
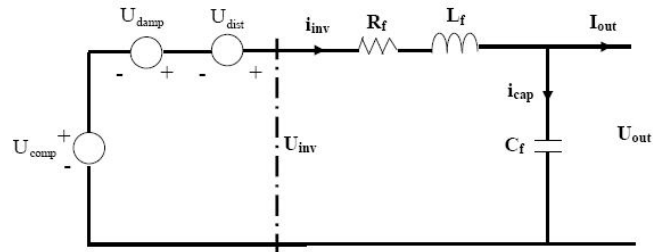

Fig.10 Equivalent circuit of the LC-filter.

Oscillation damping voltage: The oscillation damping voltage U_{damp} damps out the overshoot of the output voltage in transient state. The transfer function of the LC filter can be determined as [12]:

$$\frac{U_{out}}{U_{inv}} = \frac{\omega_f^2}{s^2 + 2\,\xi_f\,s + \omega_f^2} \qquad (9)$$

where $\xi_f = \frac{R_f}{2}\sqrt{\frac{C_f}{L_f}}$.

When the proportion C_f/L_f is designed large, the filter damping coefficient ξ_f can be large and the disturbance rejection against the load current may

also be increased. The U_{damp} can be expressed as [12]:

$$U_{damp} = K_{damp} \times i_{inv} = -a\,R_f \times i_{inv} \quad (10)$$

where K_{damp} is the control gain of the oscillation damping voltage, a is constant of proportionality.

Thus U_{damp} is proportional to the inverter current with negative damping coefficient and acts as a series resistance added to R_f which results in a total equivalent resistance of $(1+a)R_f$ in series with the filter inductance L_f. The effective system damping factor can be increased as:

$$\xi_e = (1+a)\frac{R_f}{2}\sqrt{\frac{C_f}{L_f}} = (1+a)\xi_f \quad (11)$$

Disturbance rejecting voltage: as mentioned before, the U_{damp} acts as a series resistance with LC-filter results in a voltage drop against the interface converter output voltage.

This voltage drop brings a voltage difference between the output voltage U_{out} and the injected voltage. The magnitude of the injected voltage decreases and its phase shifts from the output voltage when the load is inductive. With non-linear loads, the injected voltage will be further distorted. The disturbance rejecting voltage U_{dist} should be generated to suppress the load current disturbances:

$$U_{dist} = \left((1+a)R_f + s\,L_f\right) \times i_{out} \quad (12)$$

where i_{out} is the filter output current.

Then the total voltage drop, occurring from the oscillation damping voltage, disturbance rejecting voltage, and the filter inductance, can be calculated as:

$$
\begin{aligned}
U_{drop} &= (R_f + s\,L_f)\times i_{inv} - (U_{damp} + U_{dist})\\
&= (R_f + s\,L_f)\times i_{inv} - \left[-aR_f \times i_{inv} + \left((1+a)R_f + s\,L_f\right)i_{out}\right]\\
&= \left((1+a)R_f + s\,L_f\right)\left(i_{inv} - i_{out}\right)\\
&= \left((1+a)R_f + s\,L_f\right) \times i_{cap} \quad (13)
\end{aligned}
$$

where i_{inv} is the inverter current.

Thus the equivalent voltage drop U_{drop} of properly controlled load interface converter is only determined by its output filter capacitor current i_{cap}.

Here $s\,L_f$ can be neglected as $(1+a)R_f \gg s\,L_f$ when $\omega \langle \omega_f$, where ω is the supply angular frequency. Accordingly and from equation (12), the equivalent resistance of the filter can be expressed as:

$$R_{eq} = (1+a)R_f = 2\,\xi_e\sqrt{\frac{L_f}{C_f}} \quad (14)$$

The peak value of the inverter current can be determined from:

$$I_{peak} = \frac{\sqrt{2}\,U_{out}}{R_{eq}} = \frac{\sqrt{2}\,U_{out}}{2\xi_e}\sqrt{\frac{C_f}{L_f}} \quad (15)$$

And the injected current I_{out} is expressed as:

$$I_{out} = \frac{U_{out}}{Z_{Load}} \quad (16)$$

where Z_{Load} is the load impedance.

Since $I_{peak} \rangle \sqrt{2}\,I_{out}$, then the proportion between the filter inductance and the filter capacitance should be limited by:

$$\sqrt{\frac{C_f}{L_f}} \rangle \frac{2\xi_c}{Z_{Load}} \quad (17)$$

Then any change of filter capacitance or inductance will cause the system to lose stability. According to previous equations the system is designed as shown in table I.

Table I system parameters.

Nominal frequency = 60 Hz	Sampling time = 4 μsec
	DC-bus voltage = 70 V
Switching frequency =10 KHz	
Filter Parameters	
$L_f = 2$ mH $C_f = 600\ \mu F$ $R_f = 0.9\ \Omega$	

6. Stability Analysis with AC Loads:-

The AC system was operated with a load of 1kΩ resistive load, then the load is decreased to 500 Ω causing a step change at the load side. It can be seen that the system response in Fig.11, while not stable, is significantly under damped.

The operation of the system is investigated under this condition while using a well designed output filter and by decreasing the controller bandwidth. The results are shown in Fig.12. It can be seen that the load voltage is now over damped.

Changing the stability of the system is done by changing the parameters of equation (17). Fig.13 shows less stability response than Fig.11 as the term is decreased to half its original $\sqrt{\dfrac{C_f}{L_f}}$ of stability value. Also Fig.14 is less stable than Fig.12 as the term of stability is doubled.
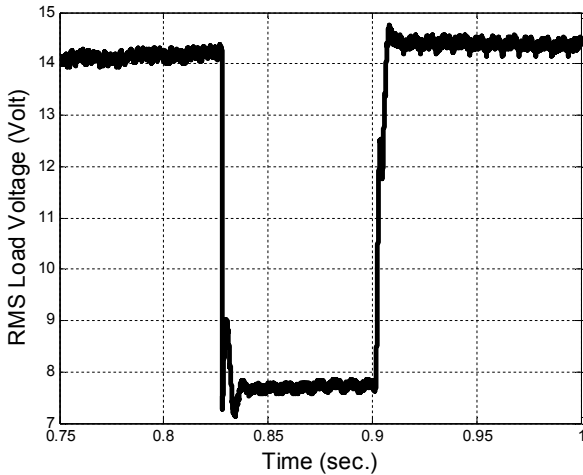

Fig.11 RMS Load voltage after step change before stabilizing the system.
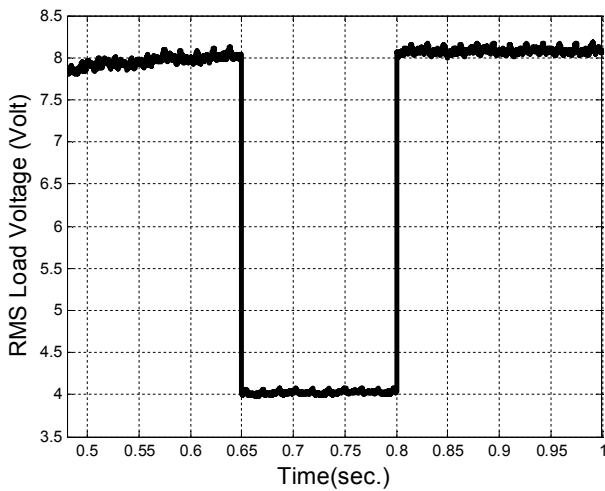

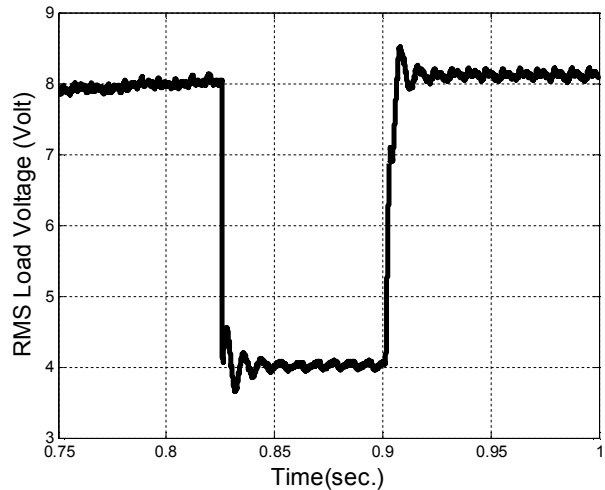Fig.12 RMS load voltage after step change after stabilizing the system .

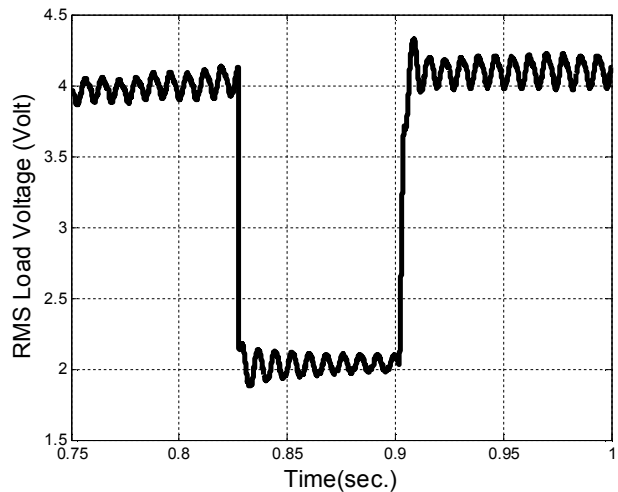Fig.13 RMS load voltage after step change with reduced stability term.

Fig.14 RMS load voltage after step change with doubled stability term .

7. Stability analysis with DC loads

The transient response of the system with DC load before and after applying a step change at the load side, are shown in Figs.15 and 16 It should be noted that these two techniques are not the only methods available for stabilizing the system.

However, input filters and a bus capacitor were used in the simulation model since these methods were the most simple means of ensuring stable operation. It must be noted that the purpose of stabilizing the system was simply to allow stable results to be obtained from the system.
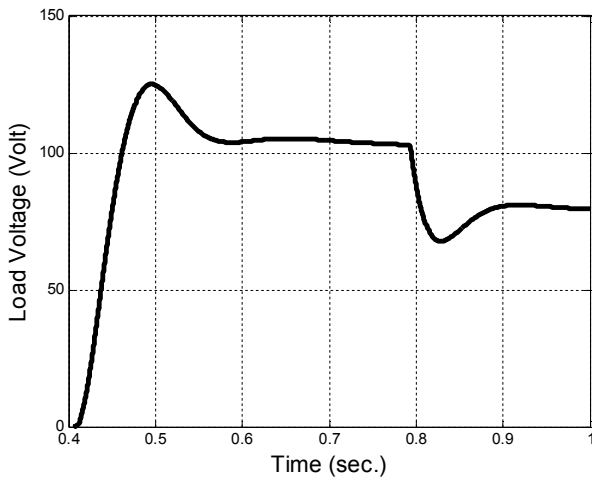
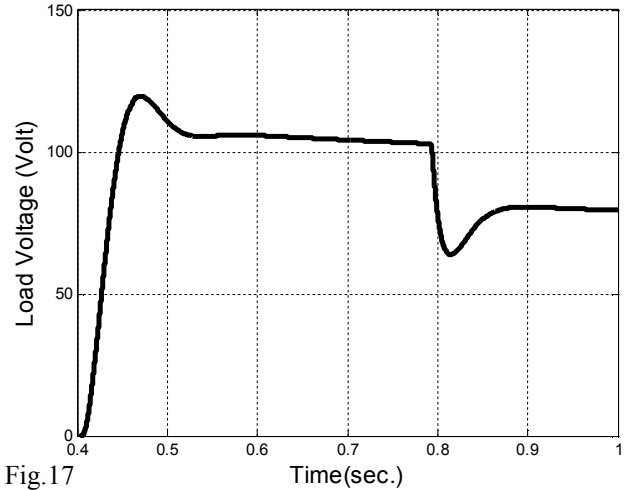Fig.15 Load voltage after step change before stabilizing the system.

Fig.17
Load voltage after step change with reduced stability term.

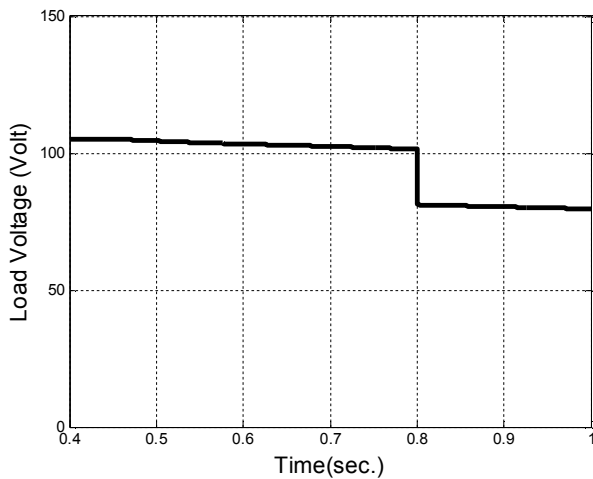
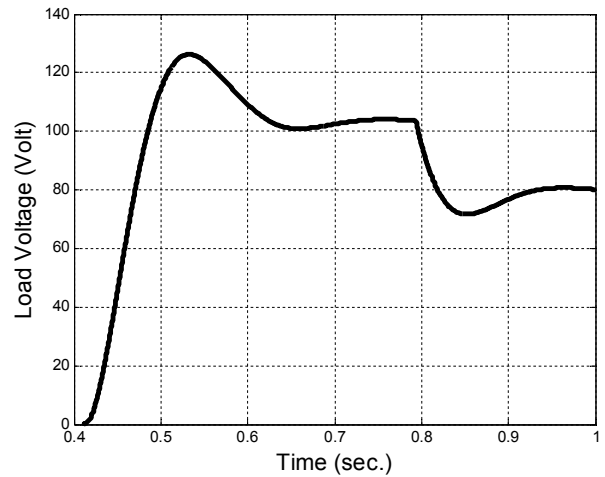Fig.16 Load voltage after step change after stabilizing the system.

Fig.18 Load voltage after step change with doubled stability term .

Changing the stability of the system is done by changing the parameters of stability $\sqrt{\dfrac{C_f}{L_f}}$, which affects the AC side then the DC side.

Fig.17 shows less stability than Fig.16 as the term of stability is decreased to half its original value. Also Fig.18 is less stable than Fig.16 as the term $\sqrt{\dfrac{C_f}{L_f}}$ is doubled.

8. Conclusion

Besides to the same principle of interfacing loads to the nanogrid, the load interface converter can be modified to work as an active filter, where the converter injects the same amplitude of harmonic voltages with an opposite sign to filter out the 5th and the 7th harmonics of the nanogrid voltage, and keeps the total harmonic distortion of the load side below the required by the standards. It is worth to mention that the isolation of harmonics and correction of the effect of the filter at harmonic frequencies do not interfere with the response of the controller at the fundamental frequency, which is still very fast.

Thus, extending the functionality of the load interface controller to work as an active filter injecting the same amplitude of harmonic voltages with an opposite sign to cancel out the grid harmonics.

As the performance of the interface converter is affected by the presence of other interface converters, due to very large over shoot that may occur in the load voltage, and also current disturbances may occur at load side. A passive filter is designed to damp out the over shoot of the output voltage and to suppress the current disturbances from the load side. A developed equation is used to describe the term of stability, changing this term leads the system to lose stability.

However, it seems interesting to point out that a considerable attenuation of low-order harmonics in the load voltage that can be clearly observed at frequencies that are lower than the resonance frequency of the filter.

The addition of the passive filter with properly designed parameters gives an enhanced performance of the interface converter both in steady and transient states.

It can be concluded that the passive filter is designed to damp out the over shoot of the output voltage and to suppress the current disturbances from the load side.

A developed equation is used to describe the term of stability, changing this term leads the system to lose stability.

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